UM High Energy Physics Memorandum March 2, 1990

To: John Peoples, Director, and the Fermilab Program Committee

From: Lawrence W. Jones, University of Michigan

Subject: Letter of Intent

Lawrence W. Jones

The request for Letters of Intent for the Fermilab fixed-target program for runs at least two years hence has stimulated us to set down concepts for experiments that might be done only in 1992 or later. This then, is not a proposal, but a letter of intent in the literal sense. We discuss below three experiment concepts.

I. A quantitative test of the Landau-Migdal-Pommeranchuk effect

The L-P-M effect refers to a lengthening of the radiation length for bremsstrahlung for high-energy electrons in high-Z, dense targets. Specifically, it predicts a decreased probability for radiation of low energy photons relative to the Bethe-Heitler prediction. The accompanying note by Todor Stanev discusses this more completely. The effect is inconsequential at low energies but very important at very high cosmic ray energies.

Although the predictions are classical QED, the only experimental tests of this process have been made at Serpukhov and with cosmic rays. In both cases the test are qualitative at best.

We would propose to use the Fermilab tagged photon facility to study quantitatively bremsstrahlung spectra from different targets. A rather simple experiment should be able to determine departures from Bethe Heitler to a few percent.

II. Hadron Inclusive Distributions at High X.

Cosmic ray processes are dominated by considerations of energy flow in nuclear interactions at high energies; and these in turn are dominated by the distributions of secondaries at high x ($x > 0.5$) in proton collisions. Unfortunately very little good data exists in this area; almost all experiments have focused on $|y_{cm}| < 3$, and the particles of interest generally stay in the beam pipe in collider experiments. Some data were taken at 100 GeV at Fermilab but only for $x < 0.8$, thus missing diffraction inelastic processes. Every major cosmic ray conference sees long discussions of the degree of breakdown of "scaling in the fragmentation region."

We intend to propose an experiment in a modest-intensity ($\sim 10^8$ per TeV "pulse") 900 GeV beam where a simple forward spectrometer could analyze final-state particles over energies $200 < E < 900$ GeV and over angles of $-1 < \theta < 10$ mr. Some particle I.D. would be needed; perhaps only a threshold Cherenkov counter. Neutrons would be studied with a calorimeter.

III. Neutron Polarization

We have previously discussed the measurement of neutron polarization in inclusive processes, in the context of the observed polarization of hyperons. This has been discussed in Fermilab P579 and in a paper submitted to the Workshop on Physics at the Main Injector (attached).

We wish to develop a proposal (perhaps a resubmission of P579) to carry out this experiment. The physics can be done at any primary proton energy between 100 and 900 GeV. However the required beam line scales directly with energy; 500 m would suffice at 100 GeV; about 4 km are needed at 800 GeV.

COMMENT

These three experiments may all be considered "back burner" activities. They will be ideal training grounds for graduate students and will continue the option of "small" physics in high energy programs. We believe that Fermilab will be the major center for student training over the coming decade and that it is essential that physics opportunities, in addition to detector R & D and mega-detectors, be available.

We note that Michigan has a particle physics user program funded at a level 3rd in the country (after Columbia and MIT) (for the most recent year for which data were available). We are also within reasonable commuting distance of Fermilab and earlier had played an active role in the intellectual life of the Laboratory.

However, it has been over a decade since a proposal submitted by a University of Michigan physicist has been accepted at Fermilab. Not surprisingly our activities have drifted away to greener pastures: CERN/LEP, SLAC/HRS and MKII, BNL, etc. We would hope to reestablish an experimental program at Fermilab, and perhaps one of these concepts would provide that opportunity.

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2 December 1987

LPM Effect in the SSC Detectors

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1. Introduction

The LPM effect (Landau and Pomeranchuk, 1953; Migdal, 1956) decreases the bremsstrahlung and pair-production cross-section in dense materials at high energy and modifies the secondary production spectra. As a results the development of electromagnetic cascades is slowed down and the cascades penetrate deeper. Although it has been estimated that the effect affects cascade development significantly only at energies $> 61.5 L_{cm}$ TeV (where L_{cm} is the value of the radiation length of the material in cm) (Stanev et al., 1982) the need to use heavy materials in the SSC calorimeters calls for a new and more detailed estimate. Another manifestation of the LPM effect is that with the decreased bremsstrahlung cross-section the electron energy loss becomes so small that at TeV energies some electrons might be misidentified as muons.

The LPM effect is due to the interference between multiple scattering and radiation when the distance between neighbouring nuclei is comparable to the radiated photon wavelength. When the two electron momenta (initial and final electron momenta for radiation processes or e^+, e^- momenta for pair production) become ultrarelativistic, the mass of the system at the vertex is negligible, so that the longitudinal momentum transfer$q_{||}$ can be very small. Conversely the distance l along which the radiation occurs becomes very long.

$$l \sim \frac{\hbar}{q_{||}} \sim \frac{2E(E-ck)}{(mc^2)^2}\frac{\hbar}{k} \tag{1}$$

where E is the initial electron energy, k is the photon momentum, and m is the electron mass. In media with sufficient density more that one atom is encountered on the distance l. These additional atoms cause multiple

Coulomb scattering of the two electron waves introducing decoherence between the two states which reduces the result of the integration to obtain the transition matrix element.

The suppression of the radiation matrix element becomes important when when the rms multiple-Coulomb-scattering angle $\langle\theta_s^2\rangle^{1/2}$ becomes larger than the scattering angle θ_r due to the radiation process. A parameter s is defined as

$$s[\xi(s)]^{1/2} \equiv \theta_r/2\langle\theta_s^2\rangle^{1/2} \sim \frac{u}{1-u} \tag{2}$$

for the case of bremsstrahlung, where $\xi(s)$ is a logarithmic factor $O(1)$ and u is the fractional energy of the radiated photon. The effect must be considered for $s \leq 1$. For pair production $s \sim 1/(v-v^2)$, where v is the fractional energy of the electron in the created pair, and since $1/(v-v^2) \geq 4$ (while $u/(1-u)$ can be arbitrarily small) , the LPM effect in pair production becomes important at energies approximately two order magnitudes higher then for radiation.

Experimentally the LPM effect has been studied in cosmic rays, where it has been only qualitatively confirmed. A quantitative result comes from a comparison of the intensity ratios of 20 to 80 MeV photons from Pb relative to Al targets and from W relative to C in experiments with a 40 GeV electron beam in Serpukhov (Varfolomeev et al., 1976).

Since the LPM effect is much stronger for electrons and in heavy materials we have calculated the bremsstrahlung cross-section and the electron energy loss in uranium. These results give an upper limit of the influence of the LPM effect in the SSC energy range.

2. Bremsstrahlung cross-section and energy loss in uranium

Fig. 1 shows the photon production spectrum in uranium as a function of the fractional photon energy. The full line represents the Bethe-Heitler spectrum, while the dash, dash-dot and dot lines show the decrease of the probability for radiation of low energy photons with the energy. At fractional photon energies of 10^{-8} the suppression is significant ($\sim$ factor of 100) even at electron energies of 1 GeV. For 10 TeV electrons the suppression is up to four orders of magnitude.

This graph is, however, somewhat misleading, since from experimental point of view the interesting parameter is the probability for radiation of photons above certain energy threshold. Such a result is shown on Fig. 2,

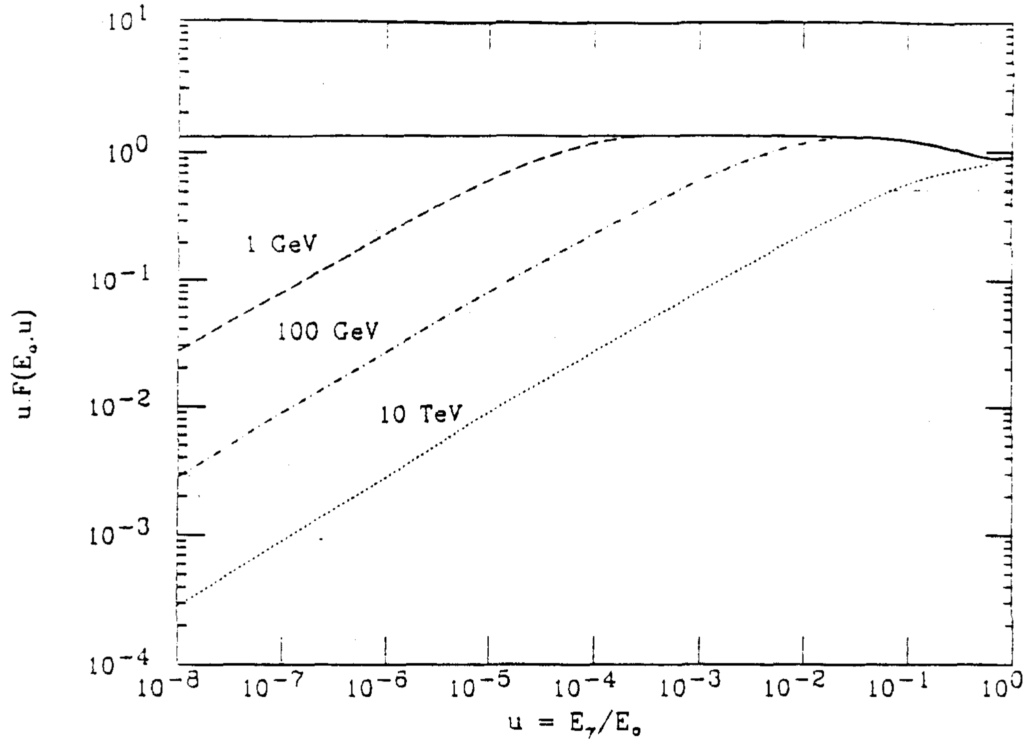

Fig.1. Differential bremsstrahlung intensities per radiation length in uranium. The solid line is for the limiting Bethe-Heitler cross-section. The energy of the incomming electron is indicated by each curve.

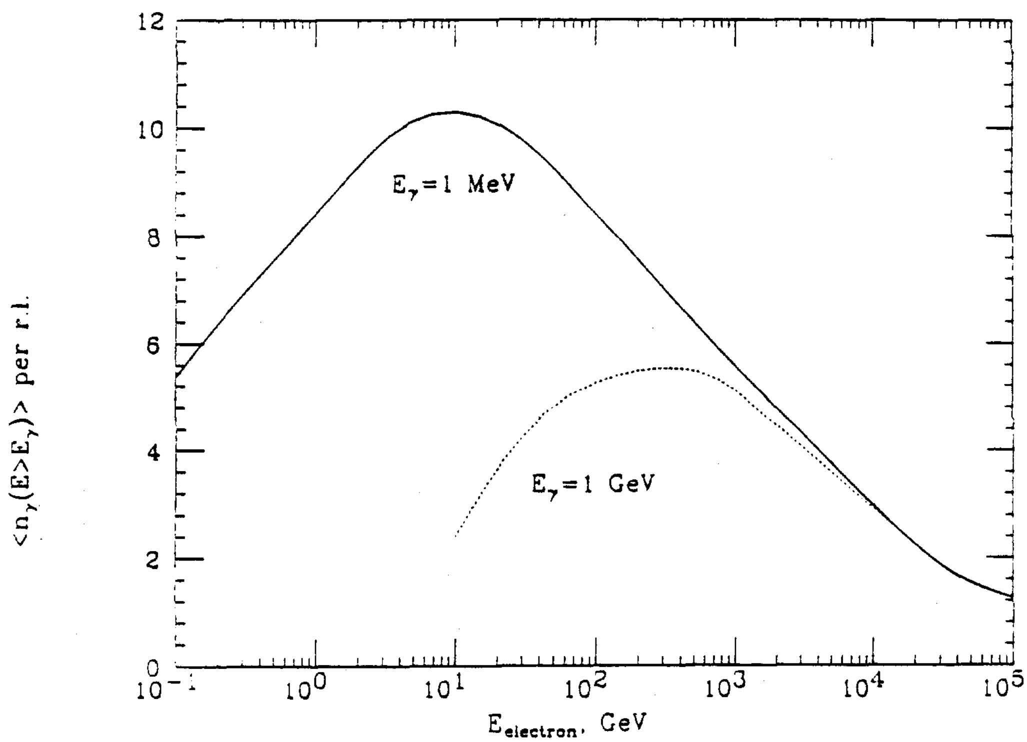

Fig.2. Average number of photons with energy > 1 MeV and > 1 GeV (dotted line) radiated on one radiation length of uranium as a function of the electron energy.

where the average number of photons radiated with energy above 1 MeV and 1 GeV is plotted versus the electron energy. Without the account for the LPM effect $\langle n_\gamma(E > E_\gamma)\rangle$ would continue to grow logarithmicaly with the electron energy. Because of the LPM effect the production of > 1 MeV photons reaches a maximum at ~ 10 GeV and significantly declines in the TeV region. At 10 TeV the production of > 1 MeV photons is lower than the Bethe-Heitler spectrum by a factor of 7.

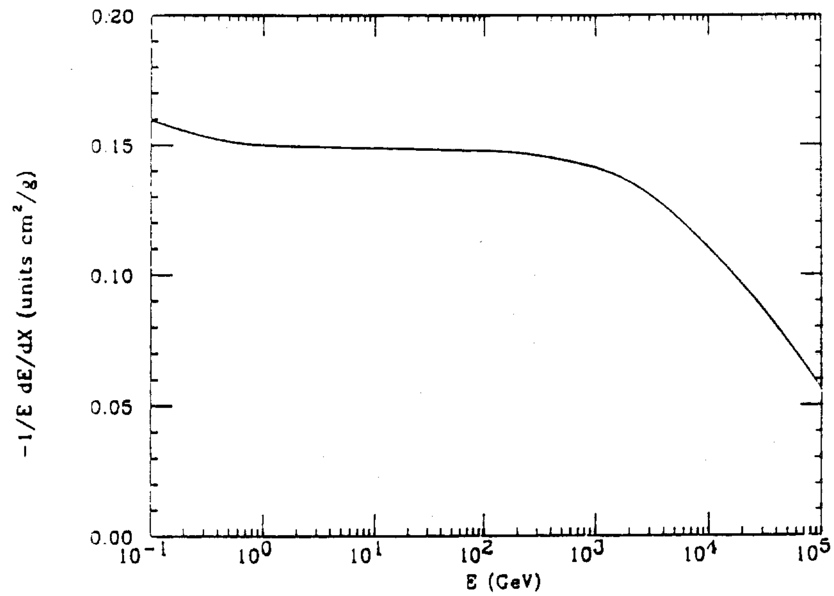

Fig.3. Fractional electron energy loss in uranium.

The decrease of the bremsstrahlung cross-section leads, of course, to a corresponding decrease of the electron energy loss. The energy loss is not affected as strongly as the cross-section because the suppression is stronger at low photon energies (note the $u/(1-u)$ factor in Eq. 2). The fractional electron energy loss per $g.cm^{-2}$ is shown on Fig. 3. The decline in the MeV region is due to the decreasing contribution of the ionization loss to the fractional energy loss. The influence of LPM effect can be detected at ~ 100 GeV but it only makes a difference of less than 30% even at 10 TeV.

3. Conclusions

The LPM effect will be present at the SSC energies, but it can hardly change the present estimates of the energy flow in the planned detectors.

Past calculations of the development of electromagnetic showers with account of the LPM effect (see Stanev et al., 1982 for other references) show that the cascade development is noticeably affected only when the cross-section for $u \sim 1/2$ is decreased, i.e. at 20 TeV in uranium. Some more subtle manifestations of the effect are possible. The angular and lateral distributions of the cascade particles in LPM cascades become narrower. The combination of the narrow angular spread and the larger depth of the first interaction will decrease the electromagnetic albedo from the detectors. Even this effect is not likely to be large, though, because the interaction products are dominated by photons, not electrons.

The decrease of the electron energy loss is not significant enough to cause misidentification of electrons as muons, unless the ratio of electrons to muons is of the order of 10^4. If a muon signal, however, has an electronic background of this order of magnitude, the LPM decrease of the electron energy loss must be accounted for in calculating the expected noise.

Acknowledgments

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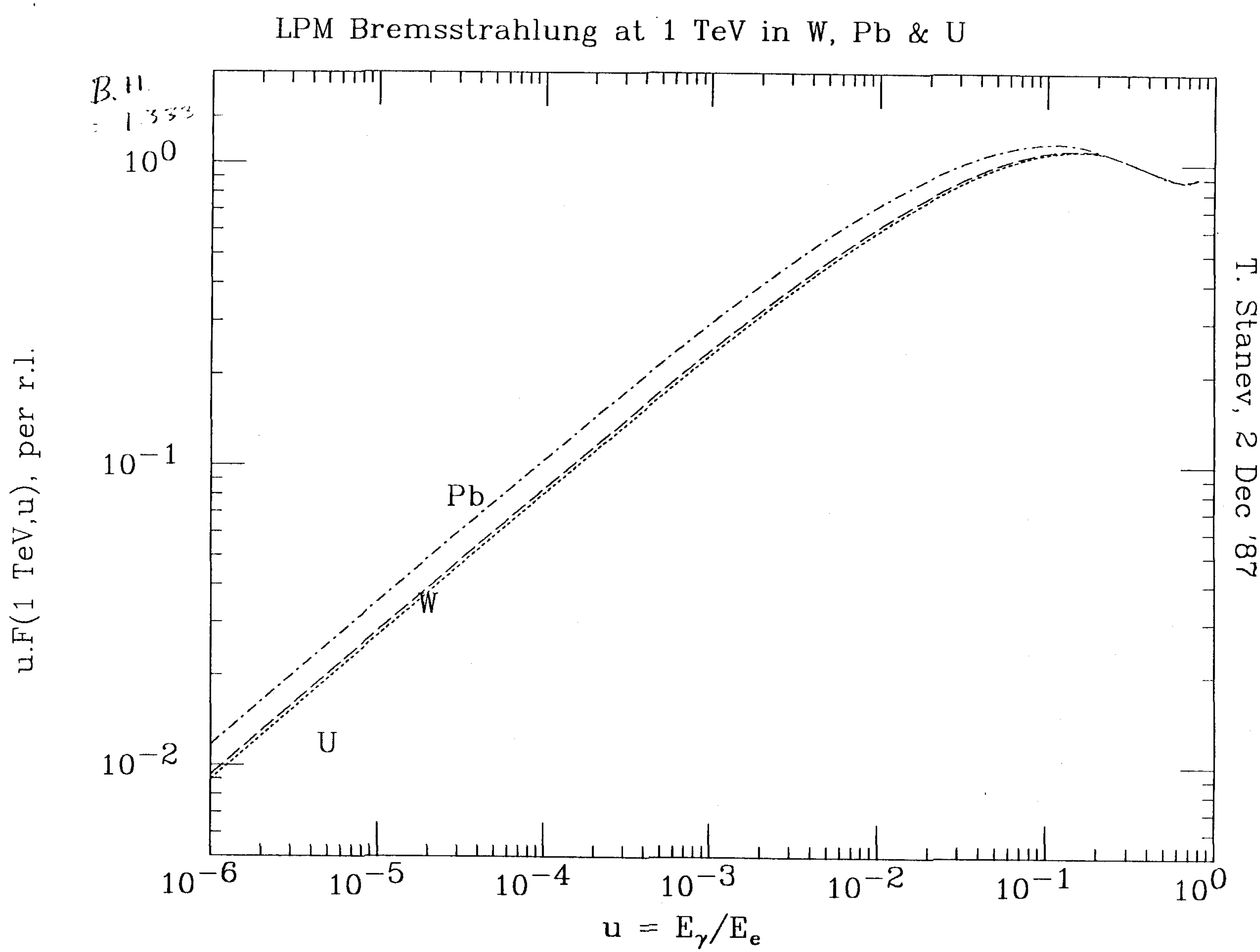
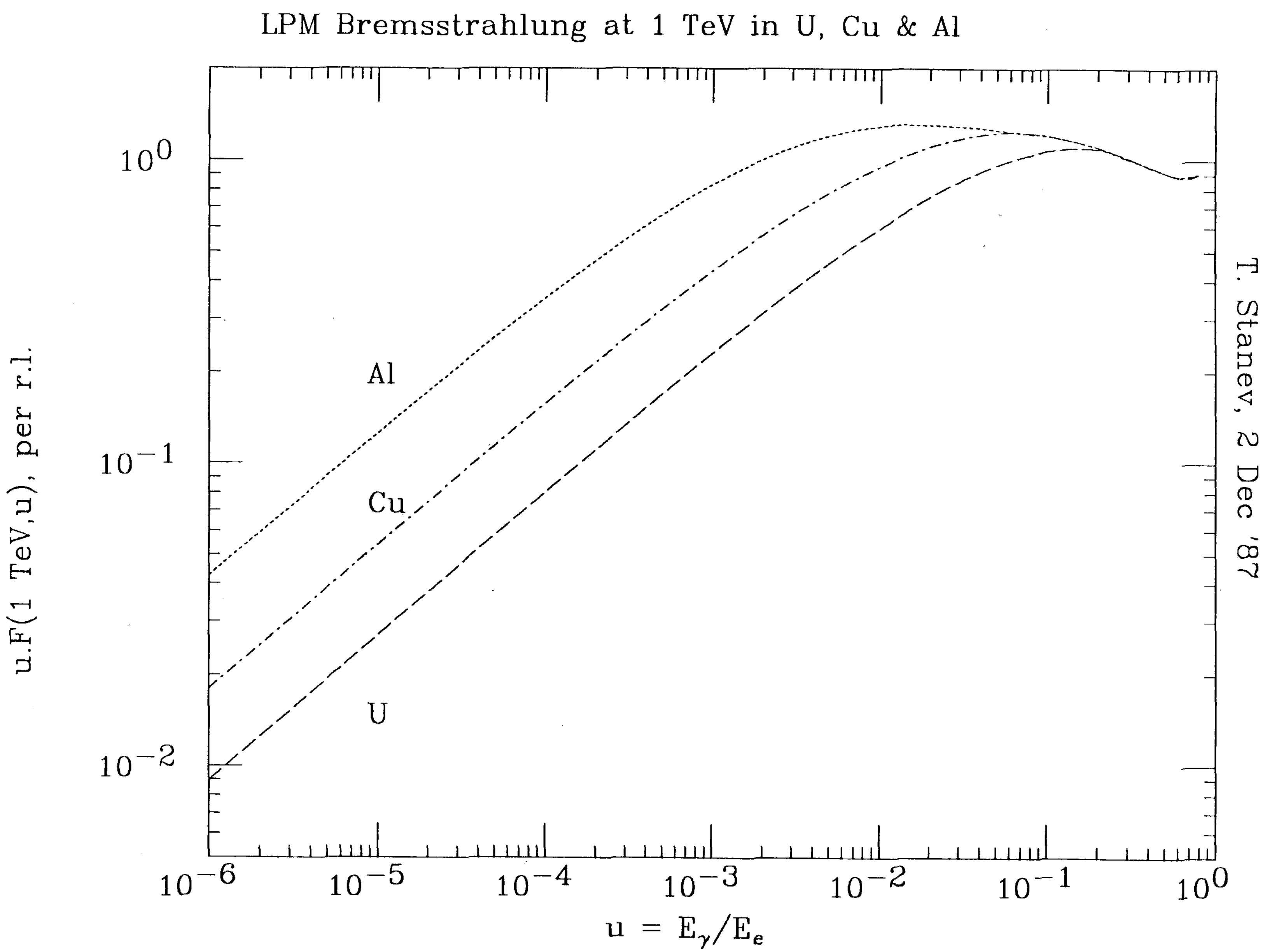
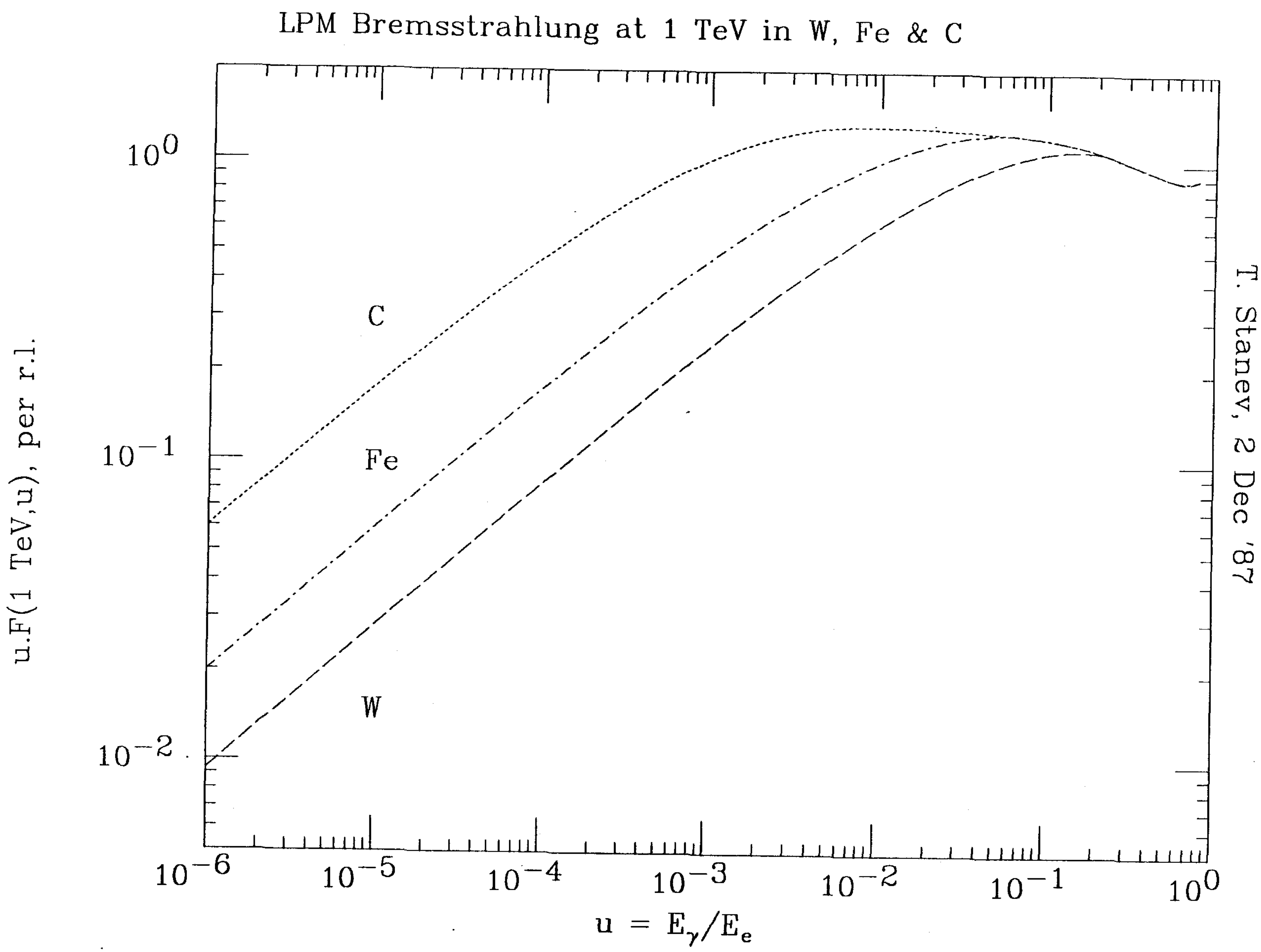
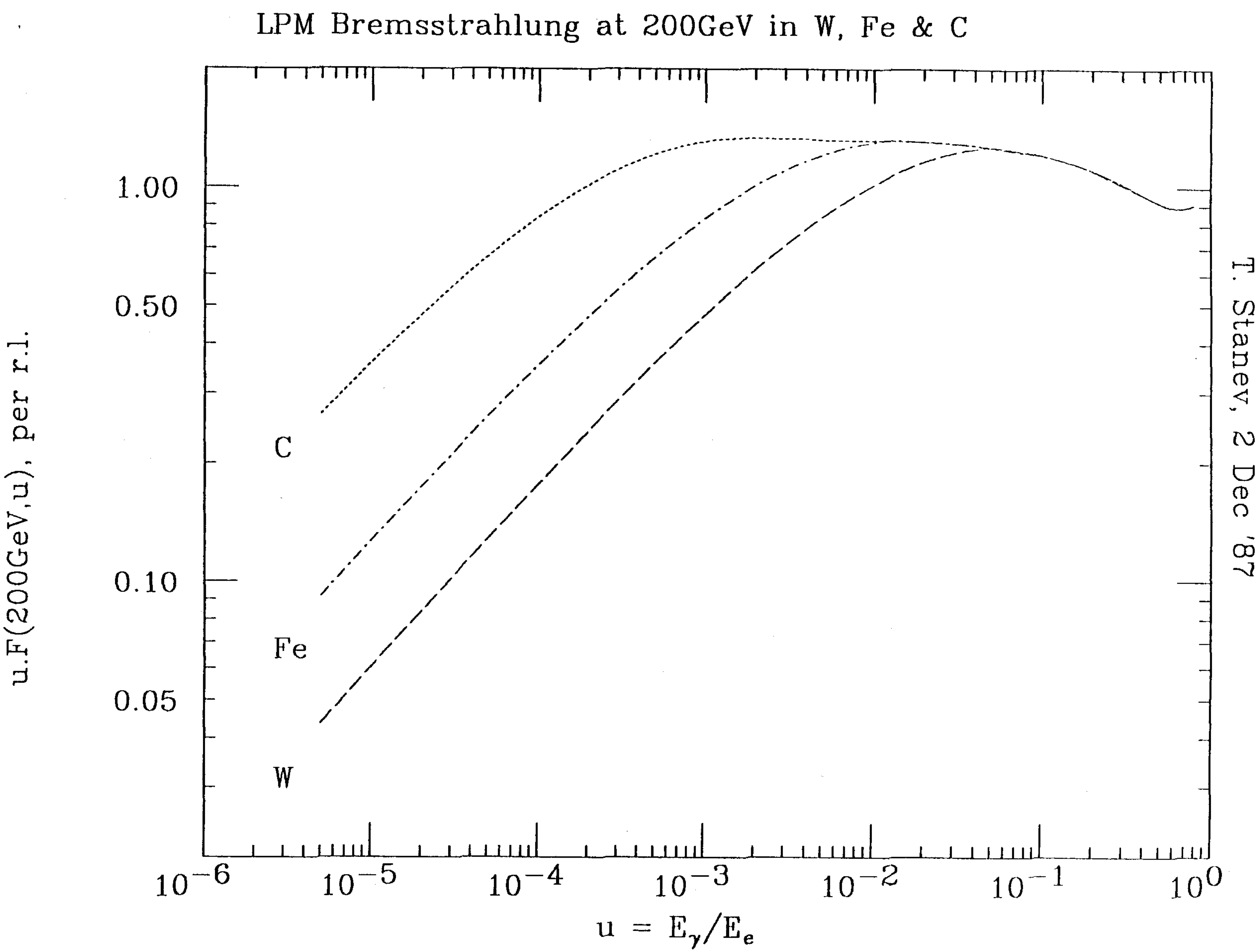


LPM Bremsstrahlung at 1 TeV in W, Pb & U
B. H.
1.333
u.F(1 TeV,u), per r.l.
10^0
10^{-1}
10^{-2}
Pb
W
U
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
$u = E_\gamma/E_e$
T. Stanev, 2 Dec '87



LPM Bremsstrahlung at 1 TeV in U, Cu & Al
u.F(1 TeV,u), per r.l.
10^{0}
10^{-1}
10^{-2}
Al
Cu
U
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
$u = E_\gamma/E_e$
T. Stanev, 2 Dec '87


LPM Bremsstrahlung at 1 TeV in W, Fe & C
u.F(1 TeV,u), per r.l.
10^0
10^{-1}
10^{-2}
C
Fe
W
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
$u = E_\gamma/E_e$
T. Stanev, 2 Dec '87


LPM Bremsstrahlung at 200GeV in W, Fe & C
T. Stanev, 2 Dec '87
u.F(200GeV,u), per r.l.
1.00
0.50
0.10
0.05
C
Fe
W
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
$u = E_\gamma/E_e$

FERMILAB-Proposal-0813

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Studies of Neutron Polarization Phenomena with 120-150 GeV Protons

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Abstract

It is proposed to have a neutral beam line from the new Main Injector to study and utilize polarized neutrons.

The polarization of neutrons is an area of strong interactions on which up until now, there is absolutely no data at multi-GeV energies. Such studies are made possible by utilizing a phenomenon first discussed by Schwinger;[1] in the scattering of neutrons from a nuclear target there is almost 100% polarization at angles where the nuclear scattering amplitude (which is almost purely imaginary) and the "Coulomb" amplitude (scattering of the neutron magnetic moment by the nuclear charge; a purely real amplitude) are equal. Such a scattering process thus provides both an effective polarizer and a convenient analyzer for neutrons. Neutron detection using an ionization calorimeter is a familiar technique, which has improved with better knowledge of calorimeter characteristics in recent years.

It is well known that hyperons are produced in proton collisions at high energy with surprisingly large polarization; up to about 30% in the case of Λ°, for example.[2] However no comparable measurement for neutrons has ever been undertaken. Neutrons are of course copiously produced in proton collisions at high energy; from inelastic interactions of protons on any nuclear target the leading baryon is a neutron about 25% of the time. Moreover the neutron spectrum is reasonably hard; from measurements at 400 GeV[3] it can be crudely fit to $(1\text{-}x)^2$, when integrated over $p_\perp$.

The program which would be attractive to pursue with the proposed new Main Injecto is therefore as follows:

First, the Schwinger Effect should be verified in neutron scattering utilizing a double scattering experiment. This would involve production of a pencil neutron beam at about 0° by the protons of 120-150 GeV on a Be target, and subsequent analysis of this polarization by a second scattering. The neutrons would then be detected with an ionization calorimeter behind a position-sensitive neutron conversion vertex detector.

Second, neutrons produced inclusively by protons of 120-150 GeV on nuclear targets (*e.g.* Be) would be studied. Here the secondary neutron beam would be defined with a collimator and the the polarization studied with a single scatter from uranium. The calorimeter would flag each neutron energy; production angles would be varied by steering the incident proton beam onto the target, so that neutron polarization could be mapped vs E_n, $p_{\perp n}$.

Third, if the neutron polarization is comparable to that of Λ°, a polarized neutron beam would be established. Using this beam, polarization experiments could be carried out on *np* total cross sections, elastic scattering, and production processes, analogous to the program of proton experiments in E704, E706, and discussed for a polarized beam in the Main Injector.

Fourth, if this program is successful and if interesting physics develops, an extension to such a polarized neutron beam from 900-1000 GeV protons from the Tevatron could be considered.

The requirements on the Laboratory for this program are quite modest. They are dominated by the need for a 600-1000 meter straight beam line from the proton target. This, however, is a very modest line; for most of its length it would be simply a buried pipe. The end station and two or three intermediate sites would need be only 10-20 feet in cross sectional dimensions and 50-100 feet long. Neutron detection requires only a good calorimeter of a few tons preceded by a vertex detector. The beam should be transported mostly in vacuum. The most critical beam elements will be the collimators, which may have apertures as small as one or two mm and lengths of up to 2 meters of iron. They must be remotely controlled to permit precise alignment. Spin rotation may be achieved easily using regular dipoles: a field integral of 5.13 Testa-meters perpendicular to the spin direction will rotate the neutron spin 180°, independent of neutron energy.

If the neutron beam is found to be polarized as much as are lambdas, a polarized neutron beam could then be produced as follows: A 120 GeV proton beam of about 2 x 10^{13} per pulse would strike a target at about 12 mr. The secondary neutron beam would then be produced at $p_\perp$ of about 1 GeV/c for E_n of 70 to 100 GeV, and a polarization (average) of about 15%. The flux of polarized neutrons utilized will then depend on the solid angle; with a rectangular aperture of 5 mr x 10 mr, the neutron flux in this window would be about 8 x 10^8 neutrons.

The motivations for focusing on the Main Injector for this program are the following: A calorimeter resolution of Δ E/E $\cong$ 50% $\sqrt{E}$ is readily achieved, corresponding to about 5% at 100 GeV. At much lower energies the poorer resolution becomes a limit to the accuracy with which P is measured. Also, at lower energies the physics is more muddled with other "soft" phenomena. However, at higher energies the beam line required, especially for the double scattering needed to study the Schwinger Effect, becomes difficult and more expensive. The polarizing/analyzing power of the Schwinger Effect is proportional to $(1-\rho^2)^{-1}$, where ρ is the ratio of real to imaginary amplitudes in NN scattering. This ratio passes through 0 at about 100 GeV, although even ρ of 0.2 results in a loss of only 4% in analyzing power.

The concept for this experiment grew out of discussions with J. Rosen, and his "Design of a High Energy Polarized Neutron Beam for NAL," a supplement to E-27. Our group developed a Fermilab proposal P-579, submitted in January 1978. Many details are contained in that proposal together with related addenda and responses to the Program Committee and laboratory management.

* Supported by the U.S. National Science Foundation.

Summarized below are a few useful relationships germane to this discussion.

Neutron-Uranium total Cross section at 100 GeV:	$\sigma(\mathrm{nU}) = 3.3 \times 10^{-24}\ \mathrm{cm}^2$
Differential n-U elastic scattering cross section at 0°:	$\left(\frac{d\sigma_e}{d\Omega}\right)_0(\mathrm{nU}) = 1.72 \times 10^{-18}\ \frac{\mathrm{cm}^2}{\mathrm{sr}}$
Neutron interaction mean free path in uranium:	$\lambda(\mathrm{nU}) = 120\ \mathrm{g/cm}^2$
Fraction of incident neutron flux scattered per sterad by a $(1/2)\lambda$ U scatterer:	$\frac{0.3}{\sigma}\left(\frac{d\sigma_e}{d\Omega}\right)_0 = 1.55 \times 10^5\ \mathrm{sec}^{-1}$
Transverse momentum for maximum polarization in n-U elastic scattering:	$p_{\perp 0} = \frac{4\pi\alpha Z\mu n}{m_n\sigma(\mathrm{nU})} \cong 2.0\ \mathrm{MeV/c}$
Scattering angle corresponding to $p_{\perp 0}$ for 100 GeV neutrons:	$p_{\perp 0}/100\ \mathrm{GeV} = 20\mu$ radians
Relative scattering angle:	$q = p_\perp/p_{\perp o}$
Polarization vs $p_\perp$ away from $p_{\perp 0}$:	$P = \frac{2q}{(1+q)^2}\,(1+\rho^2)^{-1}$

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PROPOSAL

An Experimental Test of the Landau-Pomeranchuk-Migdal Effect

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ABSTRACT

We propose to make a quantitative measurement of the Landau-Pomeranchuk-Migdal effect using the wide-band photon beam facility at the Tevatron during the next fixed-target running period. This effect, a modification of the Bremsstrahlung spectrum at low gamma energies from dense, high-Z radiators, has never been quantitatively measured, although there have been some qualitative verifications. It is of not only theoretical interest, as a departure from standard Q.E.D. Bethe-Heitler theory, but it is of practical interest as a phenomenon which becomes more relevant at SSC energies and in ultra-high energy cosmic ray experiments. Following set-up and debugging of the apparatus, only one or two weeks of data collection should be required to obtain Bremsstrahlung spectra from a variety of radiators with excellent statistics. The wide-band beam as presently set up appears ideally suited for this measurement; all that is required is a detector of photons of 100 MeV-300 GeV and appropriate pulse-height analyzers.

I. INTRODUCTION

The Landau-Pomeranchuk-Migdal (LPM) effect was predicted and quantitatively calculated by these Russian authors in the 1950's[1]. Qualitatively, it argues that an electron which radiates a photon at high energy experiences a longitudinal momentum transfer, q which is very small, corresponding to a longitudinal distance, z (from the Uncertainly Principle) which may be macroscopic; e.g. microns. If the electron is disturbed, e.g. scattered, within this distance, the radiation is suppressed. In naive language, the uncertainty principle says that the electron "doesn't know it has radiated" over this distance. Quantitatively,

$$q = p_e - p'_e - k = \sqrt{E_e^2 - m^2} - \sqrt{E_e'^2 - m^2} - k$$

where p_e, p'_e, and E_e, E'_e are the electron momentum and energy before and after the interaction respectively, and k is the photon energy. For high energy electrons, this simplifies to

$$q \simeq k/2\gamma^2,$$

where γ is E_e/m, and this holds for $k \ll E_e$. The corresponding distance, which may be called the "formation zone", is

$$z = \hbar c \gamma^2/k.$$

If, over this distance, the electron experiences multiple Coulomb scattering by an angle larger than the angle of Bremsstrahlung radiation, the radiation is suppressed. Qualitatively, a useful parameter is an energy E(LPM), where E(LPM) $= m^4 X_o/c\hbar E_s^2$ or E(LPM) (TeV) = 7.6X$_o$ (cm); E_s is 21 MeV. The photon spectrum is suppressed relative to the classical Bethe-Heitler spectrum for photon energies less than

$$k < E_e^2/\mathrm{E(LPM)}.$$

Detailed quantitative calculations have been made by Stanev and by Maciaszczyk, et al.[2]; some useful graphs are appended hereto for reference (Fig. 1). It is seen that the LPM effect causes a suppression of Bremsstrahlung spectrum for 300-400 GeV electrons on tungsten below about 30 GeV, with a suppression of a factor of (about) 4 at one GeV. The corresponding suppression in carbon is only apparent below about one GeV.

Beyond the theoretical interest (see Bell, ref. 3, for example), the LPM effect is of very practical interest in the design of detectors for energies above a TeV at the SSC. It is also very relevant in cosmic ray physics, leading to an elongation of the electromagnetic cascades from primary gammas or electrons of energies above hundreds of TeV. It should be noted that there is a corresponding LPM effect in the pair-production process, however its onset is at a higher energy.

This experiment was first suggested in a Letter of Intent from L.W. Jones to John Peoples March 2, 1990, and subsequently discussed with Taiji Yamanouchi in the spring of 1991, with a follow up letter May 14, 1991.

II. EXPERIMENT

The proposed experiment consists simply of careful, high-statistics measurements of the Bremsstrahlung spectra from a variety of radiators in the wide-band photon lab, using a 350 GeV electron beam, together with appropriate background checks, etc.

A. Beam. The required beam is the 350 GeV electron (or positron) beam as it exists entering the wide-band photon laboratory. The entire experimental setup would be upstream of the photon experiments set up in that lab. One desirable (but not absolutely necessary) modification would be to increase the length and thus reduce the field strength of the first bending magnets beyond the Bremsstrahlung radiator, in order to reduce the synchrotron radiation background. This possibility will be explored.

The electron beam intensity is about 10^8 per spill (20 seconds), which is more than enough; if anything, we would perhaps reduce this by about an order or magnitude.

B. Radiator. A wheel containing a variety of radiators will be used so that radiators may be changed easily. Radiators of about 2%-5% of a radiation length will be used. Obvious radiators of interest are dense, high-Z metals such as W, Au, Bi, U, Pb, and Ta. Contrasting low density, low-Z targets are C, Li, and Be. One or two intermediate targets such as A1, Cu, and Ag would be interesting as well. And of course one position should be empty for measurement of background; this will include synchrotron radiation plus Bremsstrahlung from windows and other residual materials in the electron beam.

By limiting the radiator to about 5%, there will be on the average only one photon radiated above 10 MeV for every 2 electrons, so that photon pileup should not be a problem.

C. Detector. The gamma detector is not yet determined, although any of a large number of existing detectors may be used; lead glass, BGO crystals, NaI, CsI, a Pb or W-scintillator calorimeter, etc. We would hope to have a detector composed of a matrix of crystals, or in any event with position resolution of the gamma conversion point, in order to identify the profile of the gamma flux.

The detector(s) output would be fed to a pulse height analyzer. The desired energies are primarily from 100 MeV to about 10 GeV, although it would be appropriate to cover up to the full energy of the electron beam (about 400 GeV). It may be sensible to use two PHA's with overlapping ranges, one connected to the anode of the PMT and the other to a dynode with a gain 20-50 times less in order to span a dynamic range of over 3×10^4.

D. Rates. With a beam of 2×10^7 electrons per 20 second spill, there would be about 10^6 photons recorded per spill, or a rate of only 50 kHz. And yet a Bremsstrahlung spectrum containing 10^8 photons could be collected in 100 beam pulses; more than adequate statistics if spread into 100 channels, even with the statistics of background subtraction.

E. Background. The largest background of concern is synchrotron radiation of the electrons in the sweeping magnets beyond the radiator (necessary to separate the electron beam from the gammas). The "critical energy" for 350 GeV electrons is 82 B(MeV), where B is the magnetic field strength in Teslas[4]. This puts an effective lower limit to the Bremsstrahlung energies which may be studied. Szadkowski and Maciaszczyk have plotted the synchrotron radiation spectrum together with the Bremsstrahlung for our situation [5]; (Fig. 2). Quantitatively, the synchrotron radiated gamma energy from 350 GeV electrons is 178 B MeV per milliradian of bend (B in Teslas). For our configuration, about 2 mr are necessary to clear the photon beam, and the total bend for the full energy electrons is 5 mr. Thus the synchrotron background to be subtracted from the Bremsstrahlung will be about 200-500 MeV per electron.

Other background effects, e.g. transition radiation, are important only at energies below several MeV, and are not important for our range of parameters.

F. Required Running Time. As noted above, a high-statistics Bremsstrahlung spectrum should require only about an hour of beam time. A reasonable target data sample is a set of spectra from 3 radiator thicknesses of a high-Z target (e.g. tungsten) and 3 radiator thicknesses of a low-Z radiator (e.g. carbon), plus single spectra from at least 2 other high-Z and 2 other low-Z radiators as well as 3 intermediate-Z targets. Interspersed among these runs should be at least 3 background (no radiator) runs and at least 3 repeat runs of two "reference" radiators. Thus we should plan on a data set of about 25 complete Bremsstrahlung spectra. At 100% efficiency, this should require less than 2 full days of running.

Realistically, we should plan on 2 weeks, preferably one week followed by a break of a week or more (to understand and correct any problems) and then a second week of serious data collection.

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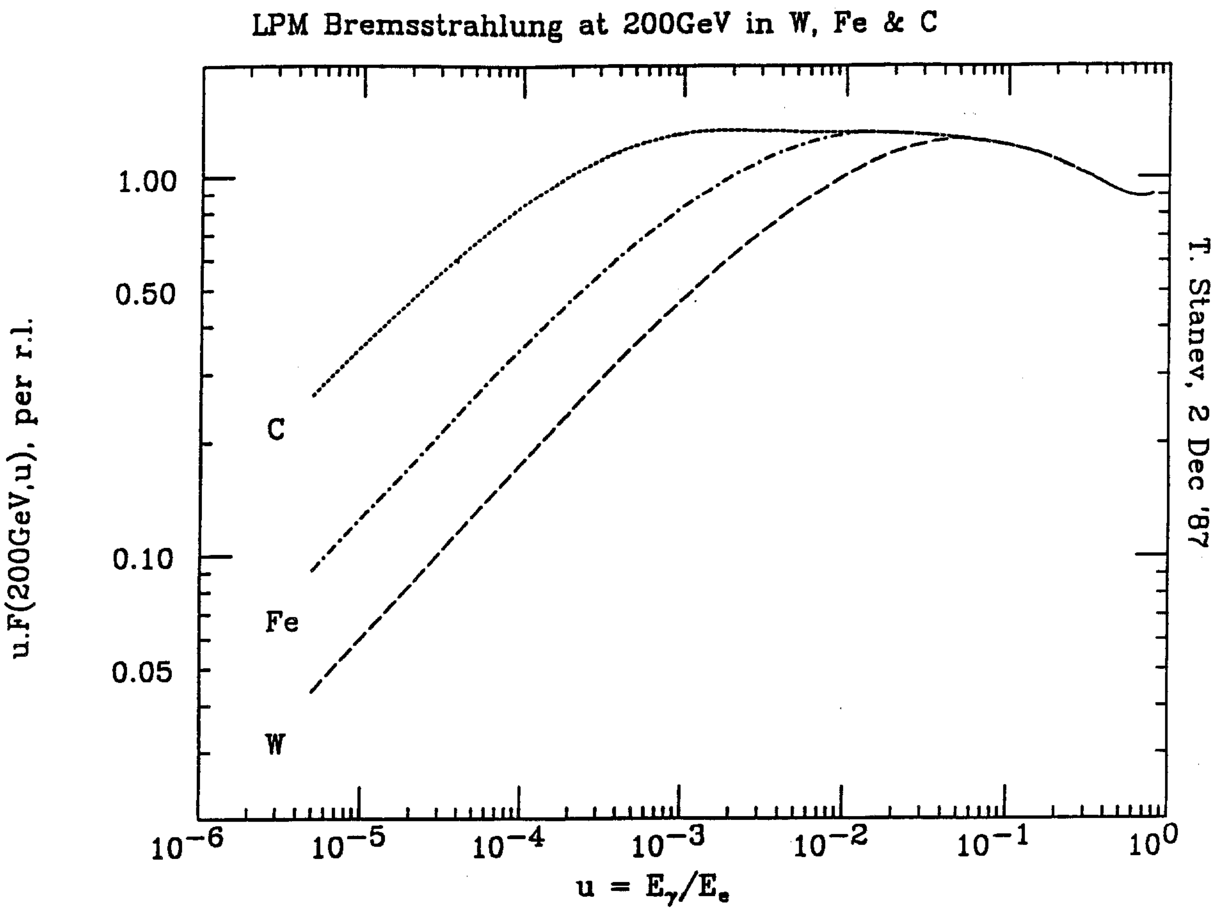

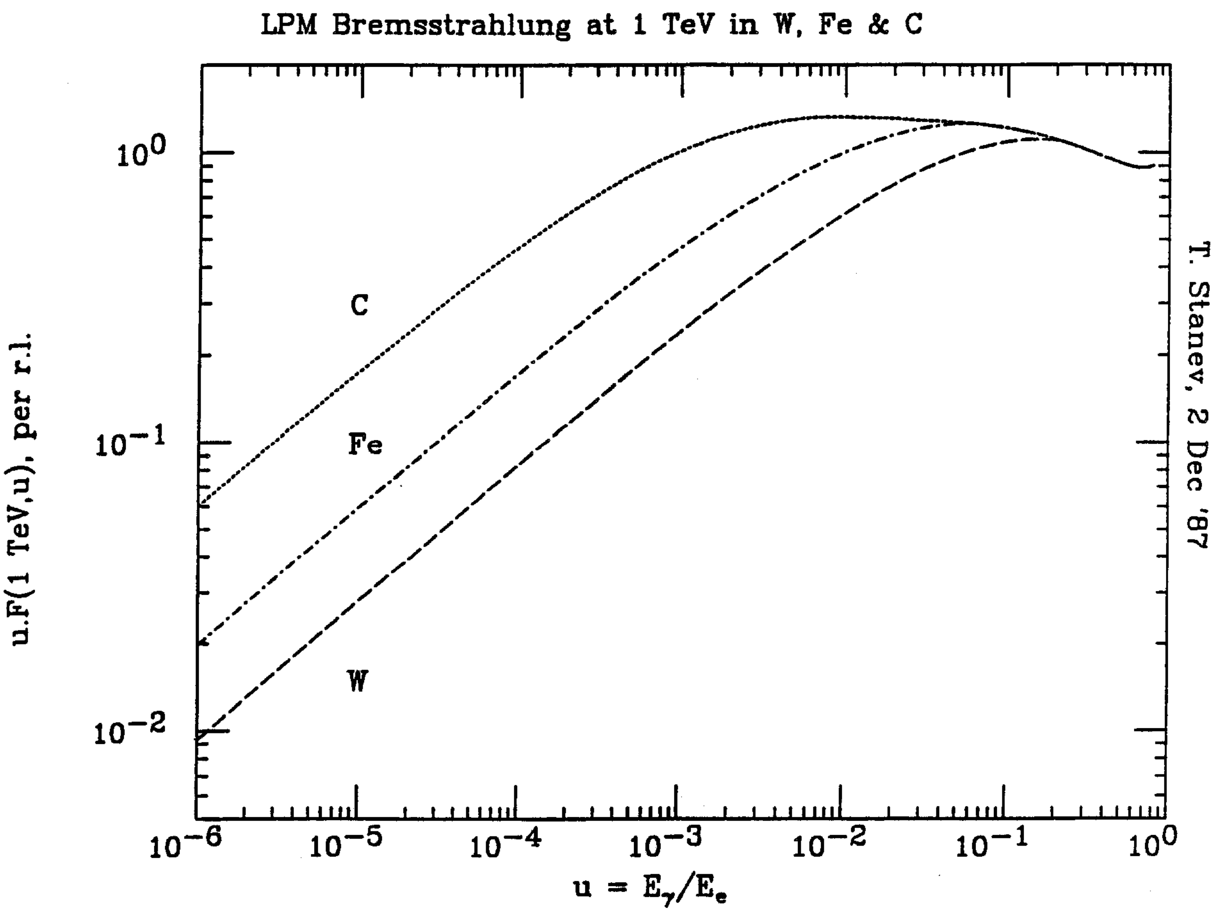

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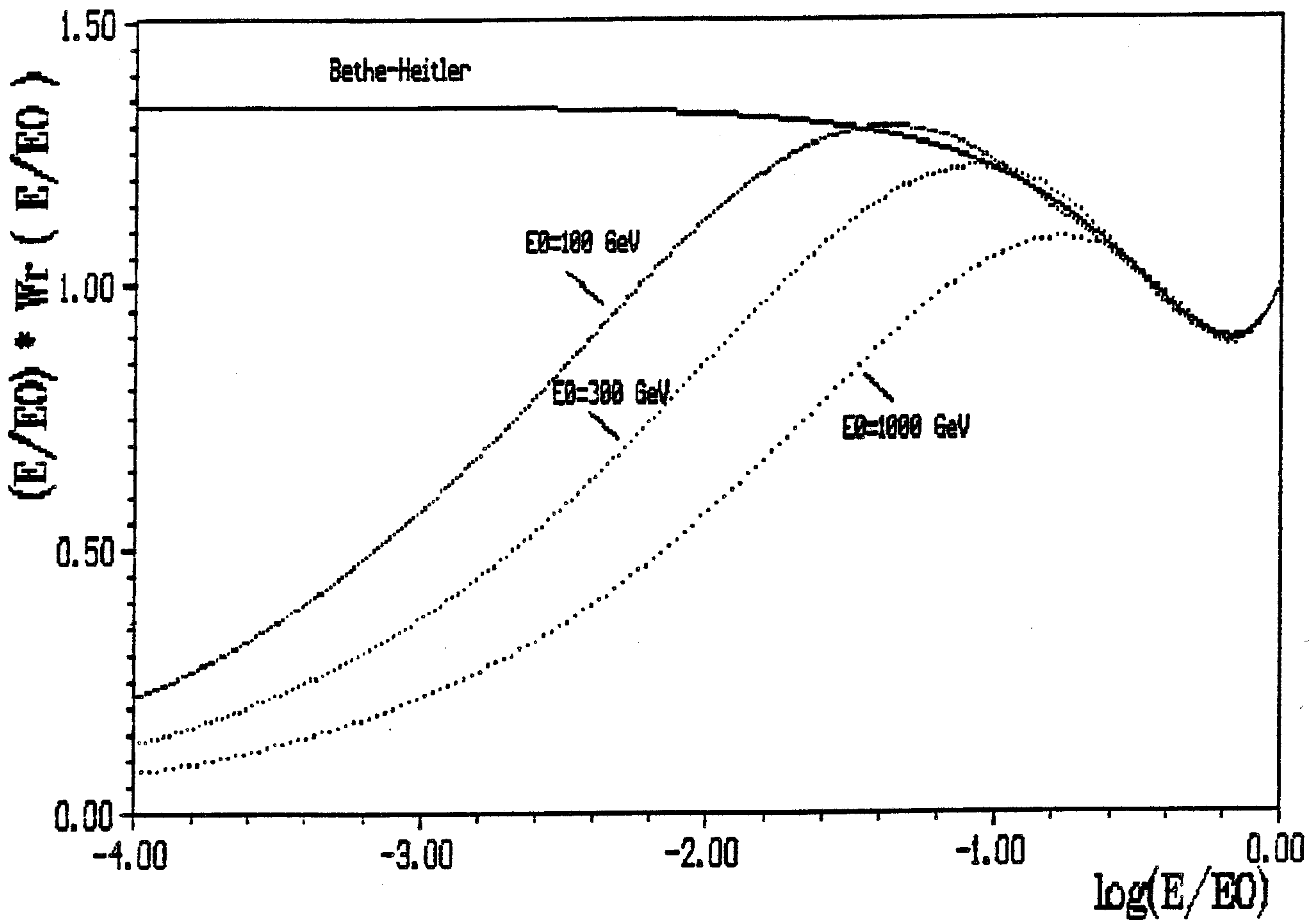

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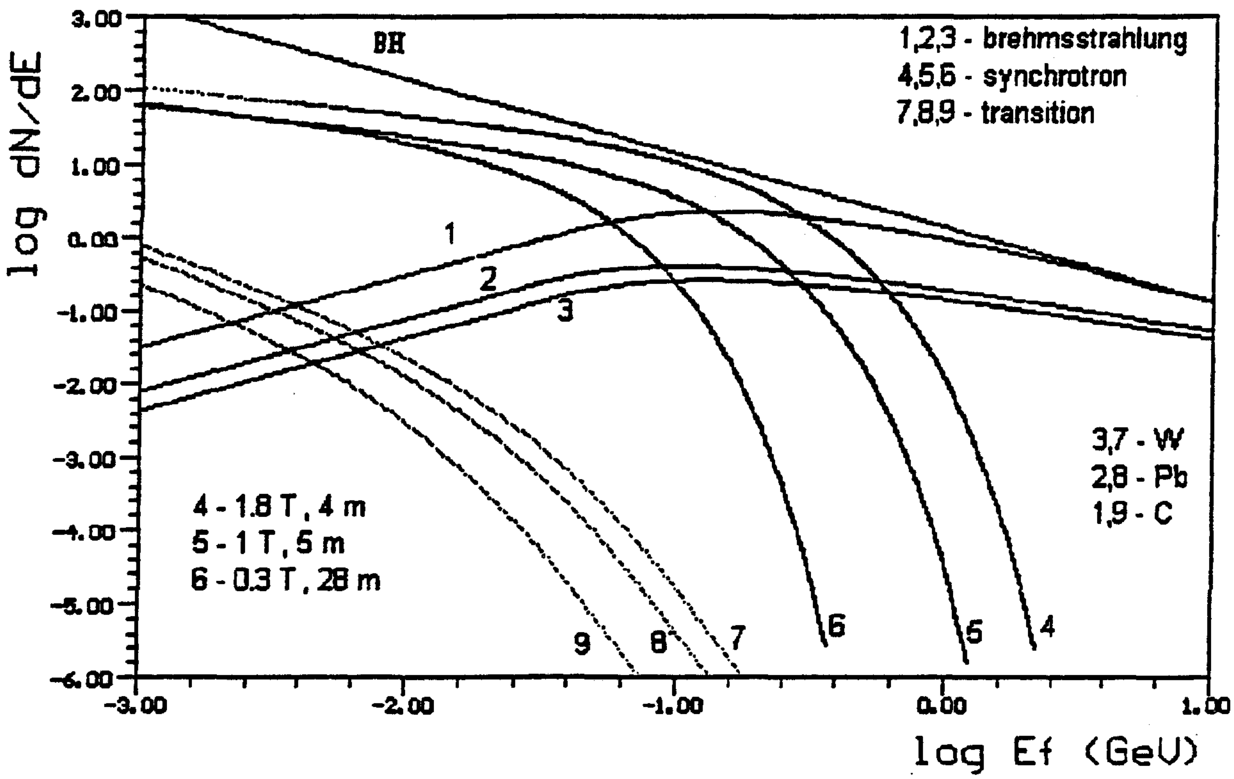

Figure 2. Comparison of the contributions of Bremsstrahlung, transition radiation, and synchrotron radiation to the gamma flux for 350 GeV electrons (from Szadkowski, et al.).

PROPOSAL

An Experimental Test of the Landau-Pomeranchuk-Migdal Effect

Lawrence W. Jones (Spokesman),
Robert C. Ball, H. Richard Gustafson, Byron P. Roe
University of Michigan

Jeffrey Wilkes, Steven Strausz, Jere Lord
University of Washington

Mary Anne Cummings
University of Hawaii

Alojzy Tomaszewski, Ireneusz Maciaszczyk, Zbigniew Szadkowski
Lódź University

ABSTRACT

We propose to make a quantitative measurement of the Landau-Pomeranchuk-Migdal effect using the wide-band photon beam facility at the Tevatron during the next fixed-target running period. This effect, a modification of the Bremsstrahlung spectrum at low gamma energies from dense, high-Z radiators, has never been quantitatively measured, although there have been some qualitative verifications. It is of not only theoretical interest, as a departure from standard Q.E.D. Bethe-Heitler theory, but it is of practical interest as a phenomenon which becomes more relevant at SSC energies and in ultra-high energy cosmic ray experiments. Following set-up and debugging of the apparatus, only one or two weeks of data collection should be required to obtain Bremsstrahlung spectra from a variety of radiators with excellent statistics. The wide-band beam as presently set up appears ideally suited for this measurement; all that is required is a detector of photons of 100 MeV-300 GeV and appropriate pulse-height analyzers.

I. INTRODUCTION

The Landau-Pomeranchuk-Migdal (LPM) effect was predicted and quantitatively calculated by these Russian authors in the 1950's[1]. Qualitatively, it argues that an electron which radiates a photon at high energy experiences a longitudinal momentum transfer, q which is very small, corresponding to a longitudinal distance, z (from the Uncertainly Principle) which may be macroscopic; e.g. microns. If the electron is disturbed, e.g. scattered, within this distance, the radiation is suppressed. In naive language, the uncertainty principle says that the electron "doesn't know it has radiated" over this distance. Quantitatively,

$$q = p_e - p'_e - k = \sqrt{E_e^2 - m^2} - \sqrt{E_e'^2 - m^2} - k$$

where p_e, p'_e, and E_e, E'_e are the electron momentum and energy before and after the interaction respectively, and k is the photon energy. For high energy electrons, this simplifies to

$$q \simeq k/2\gamma^2,$$

where γ is E_e/m, and this holds for $k \ll E_e$. The corresponding distance, which may be called the "formation zone", is

$$z = \hbar c \gamma^2 / k.$$

If, over this distance, the electron experiences multiple Coulomb scattering by an angle larger than the angle of Bremsstrahlung radiation, the radiation is suppressed. Qualitatively, a useful parameter is an energy E(LPM), where E(LPM) $= m^4 X_o / c\hbar E_s^2$ or E(LPM) (TeV) $= 7.6\mathrm{X}_o$ (cm); E_s is 21 MeV. The photon spectrum is suppressed relative to the classical Bethe-Heitler spectrum for photon energies less than

$$k < E_e^2/\mathrm{E(LPM)}.$$

Detailed quantitative calculations have been made by Stanev and by Maciaszczyk, et al.[2]; some useful graphs are appended hereto for reference (Fig. 1). It is seen that the LPM effect causes a suppression of Bremsstrahlung spectrum for 300-400 GeV electrons on tungsten below about 30 GeV, with a suppression of a factor of (about) 4 at one GeV. The corresponding suppression in carbon is only apparent below about one GeV.

Beyond the theoretical interest (see Bell, ref. 3, for example), the LPM effect is of very practical interest in the design of detectors for energies above a TeV at the SSC. It is also very relevant in cosmic ray physics, leading to an elongation of the electromagnetic cascades from primary gammas or electrons of energies above hundreds of TeV. It should be noted that there is a corresponding LPM effect in the pair-production process, however its onset is at a higher energy.

This experiment was first suggested in a Letter of Intent from L.W. Jones to John Peoples March 2, 1990, and subsequently discussed with Taiji Yamanouchi in the spring of 1991, with a follow up letter May 14, 1991.

II. EXPERIMENT

The proposed experiment consists simply of careful, high-statistics measurements of the Bremsstrahlung spectra from a variety of radiators in the wide-band photon lab, using a 350 GeV electron beam, together with appropriate background checks, etc.

A. Beam. The required beam is the 350 GeV electron (or positron) beam as it exists entering the wide-band photon laboratory. The entire experimental setup would be upstream of the photon experiments set up in that lab. One desirable (but not absolutely necessary) modification would be to increase the length and thus reduce the field strength of the first bending magnets beyond the Bremsstrahlung radiator, in order to reduce the synchrotron radiation background. This possibility will be explored.

The electron beam intensity is about 10^8 per spill (20 seconds), which is more than enough; if anything, we would perhaps reduce this by about an order or magnitude.

B. Radiator. A wheel containing a variety of radiators will be used so that radiators may be changed easily. Radiators of about 2%-5% of a radiation length will be used. Obvious radiators of interest are dense, high-Z metals such as W, Au, Bi, U, Pb, and Ta. Contrasting low density, low-Z targets are C, Li, and Be. One or two intermediate targets such as A1, Cu, and Ag would be interesting as well. And of course one position should be empty for measurement of background; this will include synchrotron radiation plus Bremsstrahlung from windows and other residual materials in the electron beam.

By limiting the radiator to about 5%, there will be on the average only one photon radiated above 10 MeV for every 2 electrons, so that photon pileup should not be a problem.

C. Detector. The gamma detector is not yet determined, although any of a large number of existing detectors may be used; lead glass, BGO crystals, NaI, CsI, a Pb or W-scintillator calorimeter, etc. We would hope to have a detector composed of a matrix of crystals, or in any event with position resolution of the gamma conversion point, in order to identify the profile of the gamma flux.

The detector(s) output would be fed to a pulse height analyzer. The desired energies are primarily from 100 MeV to about 10 GeV, although it would be appropriate to cover up to the full energy of the electron beam (about 400 GeV). It may be sensible to use two PHA's with overlapping ranges, one connected to the anode of the PMT and the other to a dynode with a gain 20-50 times less in order to span a dynamic range of over 3×10^4.

D. Rates. With a beam of 2×10^7 electrons per 20 second spill, there would be about 10^6 photons recorded per spill, or a rate of only 50 kHz. And yet a Bremsstrahlung spectrum containing 10^8 photons could be collected in 100 beam pulses; more than adequate statistics if spread into 100 channels, even with the statistics of background subtraction.

E. Background. The largest background of concern is synchrotron radiation of the electrons in the sweeping magnets beyond the radiator (necessary to separate the electron beam from the gammas). The "critical energy" for 350 GeV electrons is 82 B(MeV), where B is the magnetic field strength in Teslas[4]. This puts an effective lower limit to the Bremsstrahlung energies which may be studied. Szadkowski and Maciaszczyk have plotted the synchrotron radiation spectrum together with the Bremsstrahlung for our situation [5]; (Fig. 2). Quantitatively, the synchrotron radiated gamma energy from 350 GeV electrons is 178 B MeV per milliradian of bend (B in Teslas). For our configuration, about 2 mr are necessary to clear the photon beam, and the total bend for the full energy electrons is 5 mr. Thus the synchrotron background to be subtracted from the Bremsstrahlung will be about 200-500 MeV per electron.

Other background effects, e.g. transition radiation, are important only at energies below several MeV, and are not important for our range of parameters.

F. Required Running Time. As noted above, a high-statistics Bremsstrahlung spectrum should require only about an hour of beam time. A reasonable target data sample is a set of spectra from 3 radiator thicknesses of a high-Z target (e.g. tungsten) and 3 radiator thicknesses of a low-Z radiator (e.g. carbon), plus single spectra from at least 2 other high-Z and 2 other low-Z radiators as well as 3 intermediate-Z targets. Interspersed among these runs should be at least 3 background (no radiator) runs and at least 3 repeat runs of two "reference" radiators. Thus we should plan on a data set of about 25 complete Bremsstrahlung spectra. At 100% efficiency, this should require less than 2 full days of running.

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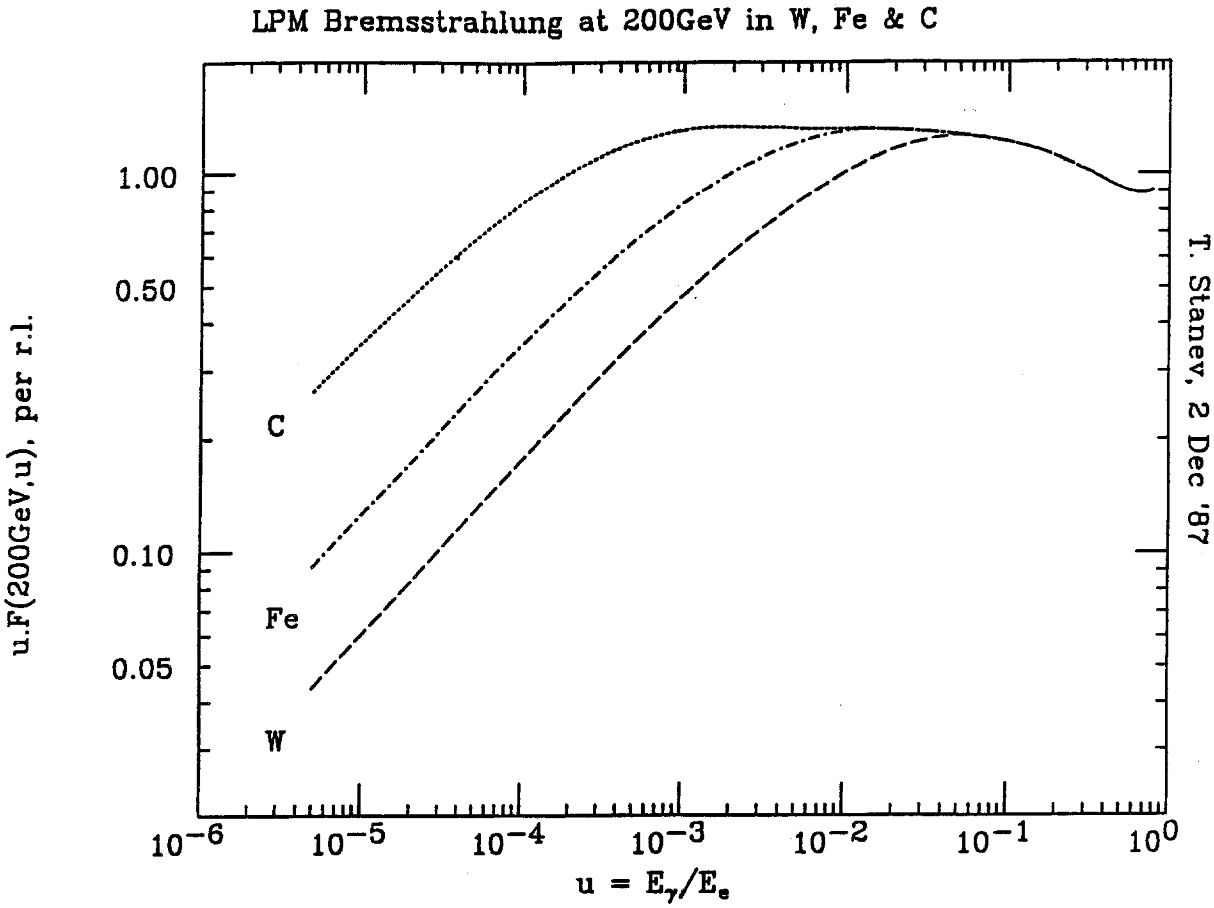

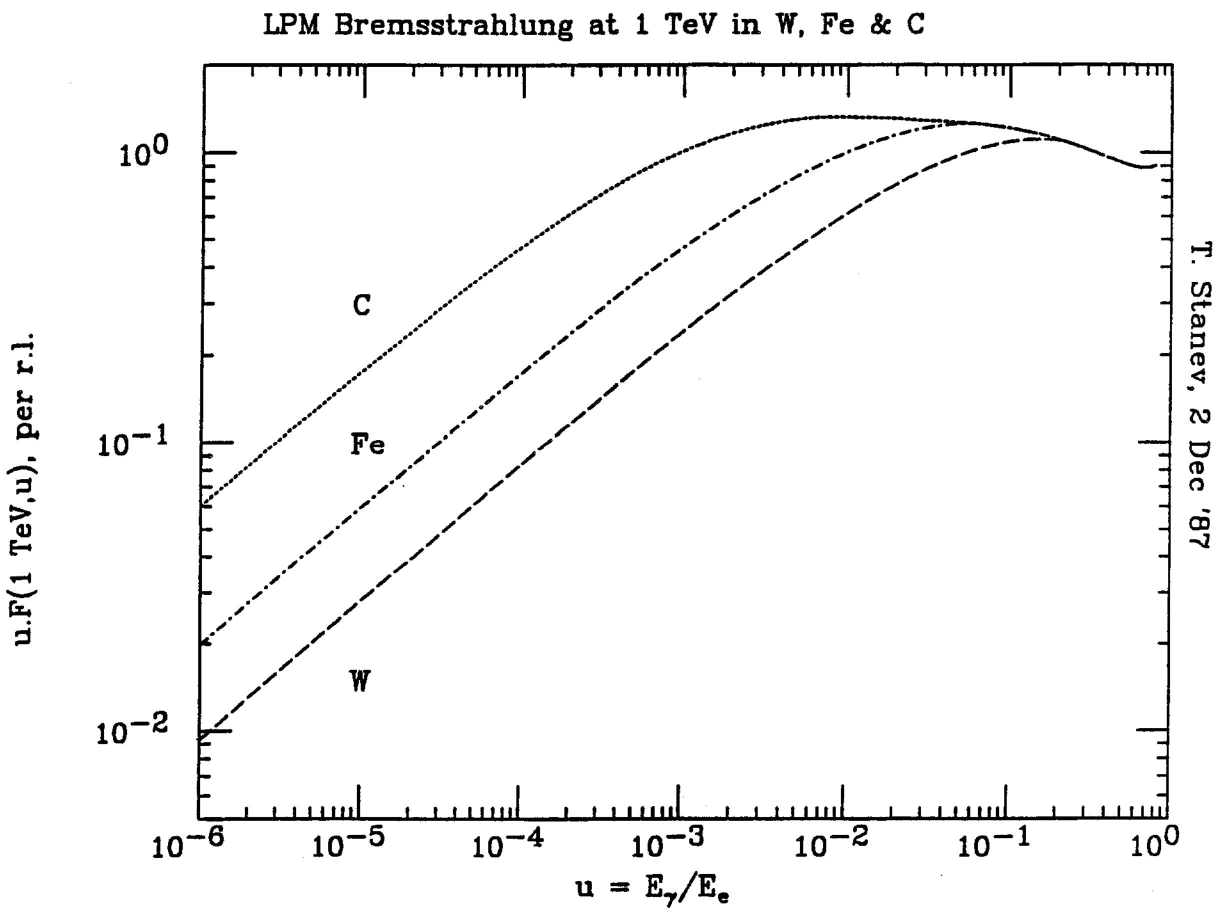

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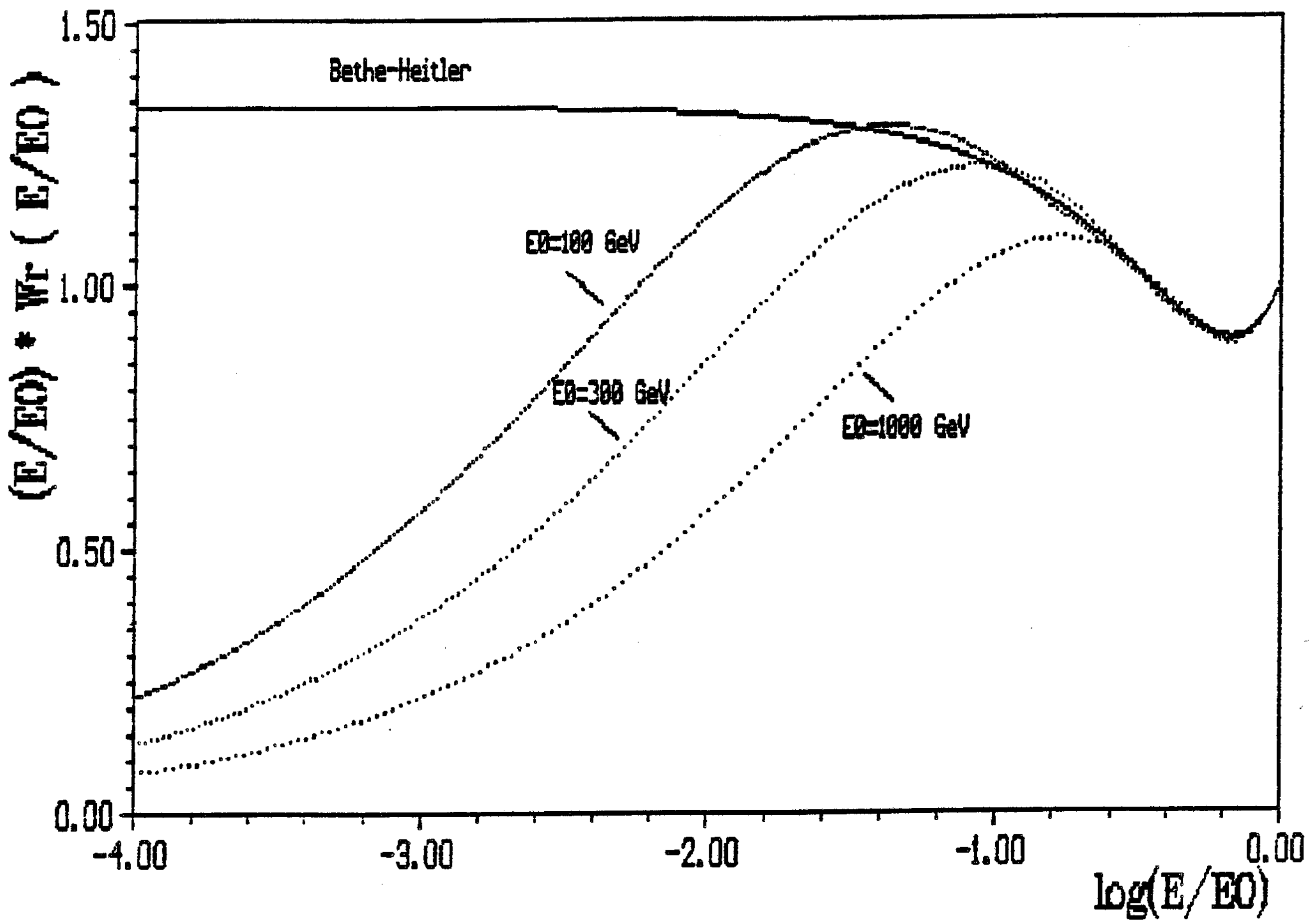

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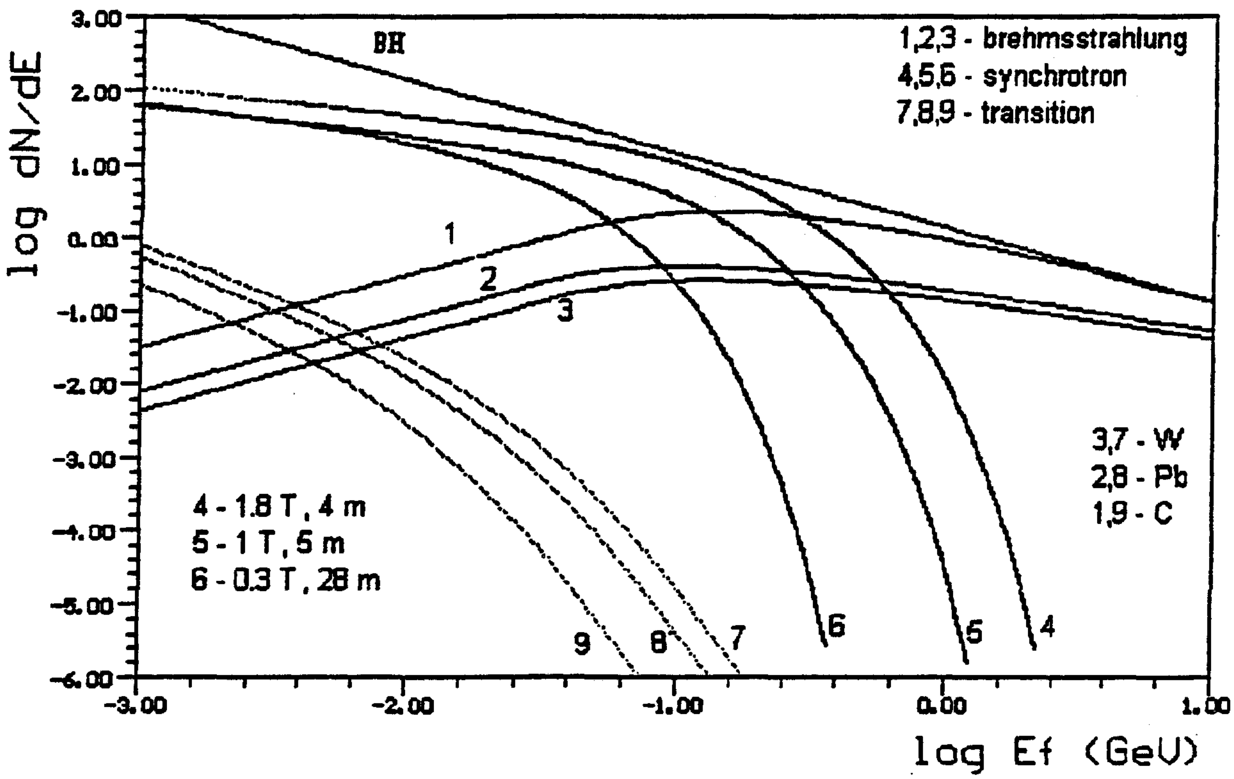

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P-813 PROPOSAL (RE-SUBMISSION)

An Experimental Test of the Landau-Pomeranchuk-Migdal Effect

Lawrence W. Jones (Spokesman),
Robert C. Ball, H. Richard Gustafson, Byron P. Roe
University of Michigan

Jeffrey Wilkes, Steven Strausz, Jere Lord
University of Washington

Mary Anne Cummings
University of Hawaii

Alojzy Tomaszewski, Ireneusz Maciaszczyk, Zbigniew Szadkowski
Łódź University

ABSTRACT

This is a re-submission of P-813, originally submitted to the Fermilab Program Advisory Committee last spring, and rejected. The timing of this re-submission is at the suggestion of Dr. Yamanouchi, in view of the delay in the schedule of the next fixed-target run.

We propose to make a quantitative measurement of the Landau-Pomeranchuk-Migdal effect using the wide-band photon beam facility at the Tevatron during the next fixed target running period. This effect, a modification of the Bremsstrahlung spectrum at low gamma energies from dense, high-Z radiators, has been measured quantitatively only at a much lower-energy (25 GeV) in a SLAC experiment which was not sensitive to details of the calculation. Quantitative understanding of this effect is not only of theoretical interest - as a departure from standard Bethe-Heitler theory, but is of practical interest as a phenomenon which becomes more relevant at progressively higher energies as encountered in ultra-high energy cosmic ray experiments. Our measurement should determine the Bremsstrahlung spectrum to an accuracy of about one percent.

From discussions at Fermilab, it appears that virtually all of the required setup and preliminary study needed for this experiment can be carried out parasitically on E-831 (photo-production of charm), and that the required dedicated beam time can be as short as only one week.

I. INTRODUCTION

The Landau-Pomeranchuk-Migdal (LPM) effect was predicted and quantitatively calculated by these Russian authors in the 1950's.[1–6] Qualitatively, it argues that an electron which radiates a photon at high energy experiences a longitudinal momentum transfer,

q which is very small, corresponding to a longitudinal distance, z (from the Uncertainly Principle) which may be macroscopic; e.g. microns. If the electron is disturbed, e.g. scattered, within this distance, the radiation is suppressed. In naive language, the uncertainty principle says that the electron "doesn't know it has radiated" over this distance. Quantitatively,

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If, over this distance, the electron experiences multiple Coulomb scattering by an angle larger than the angle of Bremsstrahlung radiation, the radiation is suppressed. Qualitatively, a useful parameter is an energy E(LPM), where E(LPM) = $m^4 X_o/c\hbar E_s^2$ or E(LPM) (TeV) = 7.6X_o (cm); E_s is 21 MeV and X_o is the radiation length (r.l.) of the material. The photon spectrum is suppressed relative to the classical Bethe-Heitler spectrum for photon energies less than

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Detailed quantitative calculations have been made by Stanev, et al. and many others; some useful graphs are appended hereto for reference (Fig. 1). It is seen that the LPM effect causes a suppression of Bremsstrahlung spectrum for 200 GeV electrons on tungsten below about 10 GeV, with a suppression of a factor of (about) 3 at 200 MeV. The corresponding suppression in carbon is only apparent below about one GeV.

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This experiment was first suggested in a Letter of Intent from L.W. Jones to John Peoples March 2, 1990, and subsequently discussed with Taiji Yamanouchi in the spring of 1991, with a follow up letter May 14, 1991.

Table 1 presents the critical energies, E(LPM) and the threshold energies E(T) for different elements and different energies. The graph (due to Stanev) presented in Figure 1 shows the magnitude of the LPM effect in the comparison between C, Fe, and W for 200 GeV incident electrons.

A significant issue is the difference between the original Landau-Pomeranchuk calculation[1,2,3] and the more detailed calculation due to Migdal.[4,5,6] At Michigan and at Łódź the spectra for 250 and 350 GeV electrons incident on 10% radiation length targets have been calculated for both expressions as well as the Bethe-Heitler formula. Some of these results are presented in Figure 2, 3, and 4. These are Monte Carlo calculations for beam on radiators of 0.1 r.l. thickness, plus 0.05 r.l. background. That the spectrum rises, even for Bethe-Heitler is due to the pile-up of gammas. Thus two lower energy gammas are counted as the sum of their energies, if radiated by a single electron. This depopulates the lower energy bins in favor of the higher energy bins. The ratio of the Migdal to the approximate Landau-Pomeranchuk for Tungsten ranges up to 10% (Table 2, from Szadkowski's calculations).

II. EXPERIMENT

This experiment consists simply of careful, high-statistics measurements of the Bremsstrahlung spectra from different radiators in the wide-band photon lab, using the 250-350 GeV electron beam, together with appropriate background checks, etc. From discussions with members of the E-831 collaboration (P. Garbincius and J. Cumalot), it appears practical to observe and study the beam characteristics and background problems during routine operation of E-831 by tapping into signals from their beam-end calorimeter. Further, the amount of material in the beam in E-831 appears sufficiently small that P-813 can observe gammas at the down-stream end of E-831 without any perturbation of that existing experimental apparatus or beam line.

A. Beam. E-831 plans to run with a 250 GeV electron beam (rather than the previously-discussed 350 GeV) in order to obtain a higher gamma flux. P-813 would also be able to take data at 250 GeV, although at a lower beam rate and with different radiators. The beam intensity can be easily reduced by detuning or turning off the focusing quadrupoles in the up-stream half of the electron beam, The lower energy, still an order of magnitude greater than that of the SLAC experiment, will alleviate the synchrotron radiation background, although it will reduce the LPM effect somewhat also. It would be desirable to take some few data runs at 350 GeV also (within the constraints of the requested one week of dedicated running).

The material upstream of the radiator in E-831 will be 0.044 radiation lengths, and the material in their experiment between the radiator and the beam-ending gamma calorimeter is 0.0.021 radiation lengths.

It appears practical to shunt the first bending magnets beyond the radiator in order to reduce the synchrotron radiation from the first milliradian of bend (that angular aperture seen by the detector) significantly. This factor of two reduction of the field in the first magnets is easily compensated by a 20% greater field in the remaining magnets, and the shunt solution to this problem requires no additional power supplies or other hardware modifications.

As noted below, the rate of data collection for P-813 will be only about 1 kHz (limited by readily-available ADC's, such as the LeCroy 2249), hence we can operate with a low-intensity beam; one or two orders of magnitude less than E-831 will utilize. However, E-831 could continue to operate their experiment during our data collection, as we will not interfere with their system. Whether we could take useful data in electron beams corresponding to their (approximately) 10 Mega-Hertz rate is uncertain. Obviously it is in our interests to operate as compatibly as possible with that group in order to maximize our own data set.

B. Radiator. The E-831 Bremsstrahlung target is mounted on a 4-position wheel. We would mount our radiators on a wheel interchangeable with theirs. They utilize a 20% radiation length lead radiator; we would utilize 10% radiators of C and W and nothing (background) as our primary targets, with shorter runs using U (if readily available), Pb, Fe, and Be. We would also like to make a special target of 0.1 r.l. Fe mounted between poles of an electro-magnet, to permit us to study the magnetic analogue to the LPM effect[8] (never completely calculated).

C. Detector. The E-831 group plans to build a calorimeter of plates of fused-silica of 1/4 in. or less thickness separated by lead plates of the same thickness and built up to 25 or more layers of each. The Cherenkov light from the silica would be collected from the edge of the plates with suitable light-guides. With this detector there should be 100 or more photo-electrons per GeV of gamma energy loss (the major uncertainty comes from the efficiency of light collection from the silica; this figure assumes 6%), quite sufficient for adequate resolution at and above one GeV for P-813. If this experiment is approved we would gladly assist the E-831 group in working on this detector. It should be noted that radiation damage is a serious consideration for E-831; at their beam intensity, lucite, scintillator, and lead-glass yellow rapidly. For our short, low-intensity experiment, this is not a serious problem. However, our compatibility with E-831 and our data collection efficiency would surely be aided if a common gamma detector were utilized. If this is not possible, we will furnish our own detector. We already have Pb-scintillator calorimeter units, Pb-glass, and have access to BGO and other crystal scintillators appropriate for this job.

The calorimeter will be used to collect data from 100 MeV to 400 GeV and data would be sorted into bins of about 20% width (four channels over a factor of two energy), hence requiring about 40 - 50 channels. The bins of constant energy fraction are a convenience for this experiment as they would be equally populated for a 1/E Bethe-Heitler spectrum. Our calculations and graphs (Figs. 2, 3, 4) use such a binning.

D. Data Collection. An electron beam of 10^7 per spill would permit accumulation of a spectrum of 10^6 gammas in 100 spills (less than 2 hours), with a digitization rate of 1 kHz. This would provide about 25,000 counts in each of 40 channels (for a 1/E spectrum) or about 0.6% statistics per bin; 0.3% statistics over each factor of 2 in energy. Our Monte Carlos show that the energy resolution of the detector is not critical; essentially no difference was seen between a "perfect" detector and one with 15% resolution. The LPM effect is only quite slowly energy-dependent. We would propose to use LeCroy 2249 ADC's as noted in the circuit diagram of Figure 5.

Figures 2 is the L'od'z Monte Carlo calculations of the spectra from 10^6 electrons of 350 GeV incident on: 5% r.l. of Be (regarded as the invariant upstream background), 5% r.l. Be plus 10% r.l. C, and 5% Be plus 10% U, in each case including synchrotron radiation from 2 mr of bending in a 0.5T field.

E. Background. From Figure 2 it is apparent that the synchrotron radiation background is relevant. The synchrotron radiation produces 178 B MeV per milliradian of bend for 350 GeV electrons (B in Teslas), hence serious interpretation of the Bremsstrahlung data will be restricted to energies above 500 MeV. For 250 GeV electrons the effect is $(250/350)^4$ less serious (for the same geometry), or less than 50 MeV for our case. Synchrotron radiation due to the last upstream bend of the electron beam and due to the maximum field seen by the electrons in the focusing quadrupoles has been studied and is small compared to that due to the bend just beyond the radiator.

The background due to Bremsstrahlung from upstream material in the beam is included in our Monte Carlo calculations, and does not pose a problem. The 2% r.l. of material in the experiment between the radiator and the calorimeter will absorb gammas at a rate virtually independent of energy; a veto ahead of the calorimeter will handily reject electrons from upstream conversion, and no problem is expected from this source.

F. Required Running Time. A high-statistics Bremsstrahlung spectrum will require one or two hours of beam time. For the cleanest test of the LPM effect, we will concentrate running on targets of 0.10 r.l. of W and C plus background (the 0.05 r.l. of low-Z material in the electron beam). It is also desirable to take data with other low-Z targets, e.g. Be, and with other high-Z targets, e.g. Pb and U, as well as intermediate Z such as Fe and Ag. Another set of runs should be taken with thinner radiators of the primary targets of W and C; 0.05 r.l., for example. All of these runs add up to less than 20 separate runs, capable of completion in less than two full days. We also propose to study the magnetic analogue to the LPM effect, wherein a piece of iron 0.1 r.l. thick is the radiator target in its magnetized and unmagnetized states[8] (Table 3). This will add 4 additional runs.

Additional running with 350 GeV electrons on the principal targets (0.1 r.l. W and C) will be undertaken, if no problems exist in raising the beam energy, to the extent running time permits.

At CERN Uggerhoj and colleagues[9] have studied Bremsstrahlung from single crystals of Ge, Si and C (diamond). With the low intensity electron beam it would be possible to look at these effects at Fermilab, wherein the Bremsstrahlung beam is greatly enhanced at high energies. We will consult with the E-831 group concerning whether studies of these effects merit study by us. The normal electron beam for E-831 has too great an angular divergence to cleanly study these effects.

Altogether, our request of one week of dedicated beam control appears adequate, assuming that we can understand the beam and detector in a 100% parasitic mode as discussed above.

G. Data Analysis. By now we have run a large number of Monte Carlo simulations, with various targets, target thicknesses, backgrounds, and synchrotron radiation background conditions. There is no problem in running other possible configurations which might prove relevant. One interesting feature of the data we learned from these simulations was the observation that, at low energies (ca. 1 GeV) the spectrum from the background runs had a greater bin occupation than that from the same background plus a radiator in the beam, for the same number of incident electrons. Upon reflection, this is reasonable; the same electron which had radiated an 800 MeV gamma in the radiator-out run may do this also in the radiator-in run, but may subsequently radiate a higher-energy photon; the detector, of course, records the sum of the two energies.

There are two ways to handle data from an experiment such as this. One can either take the data and unfold it to separate thick-radiator effects, synchrotron radiation, and upstream beam background effects and then compare the reduced data with theory. Or one can simulate the thick target and other effects in a Monte Carlo calculation and compare the simulation with the data. For our experiment, this latter procedure appears simplest and preferable.

III. COLLABORATION

The spokesman for this experiment is Lawrence W. Jones from the University of Michigan. Other collaborating Michigan physicists will be Professor Byron P. Roe, Dr. Robert C. Ball, and Dr. H. Richard Gustafson. Dr. Gustafson is resident at Fermilab about half time, and can serve as liaison to the group during the preparation of the experiment.

A major collaborating group is from the University of Lódź in Poland. There has been ongoing discussion with Professor Tomaszewski and members of his group over the past two years, and they are eager to contribute and participate. They have considerable familiarity with the LPM effect from their cosmic ray work, and have both theoretical and experimental expertise to contribute. We will apply to the NSF Office of International Programs for financial assistance to facilitate their participation. This is obviously a chicken-and-egg situation, in that the approval of this grant will be greatly enhanced by approval of the experiment, and experimental approval will be enhanced by their guaranteed participation.

Other collaborators will be Dr. Mary Anne Cummings of the University of Hawaii group, currently working on D0, and a recent Michigan Ph.D. Also Professor Jeffrey Wilkes, Professor Jere Lord, and Dr. Steven Strausz of the University of Washington (Seattle). Dr. Wilkes and his group have also been active cosmic ray experimentalists and have been sensitive to the impact of the LPM effect on high-energy cosmic ray observations. Professor Wilkes is a former colleague of L.W. Jones in the Echo Lake cosmic ray experiments some years ago.

It is expected that graduate students from at least Michigan and perhaps Washington will join this experiment; it is an ideal thesis-sized project.

IV. OTHER EXPERIMENTS

There have been reported measurements of the LPM effect. From the study of the development of electromagnetic cascades in cosmic ray emulsion chambers, a qualitative verification of the effect was obtained[10]. An experiment in a 40 GeV beam at Serpukhov in the 1970's has been published,[11] but, because of background problems, was only partly successful. Last year at SLAC Spencer Klein and collaborators made a clean, quantitative measurement of the LPM effect with a 25 GeV electron beam, to the extent that the effects are apparent at such a low energy.[12] They observed the very low energy dielectric suppression (to which we will not be sensitive) but were not sensitive to the differences between the earlier Landau-Pomeranchuk theory and the detailed Migdal calculation. We will remain in close contact with Klein and his colleagues to learn from their experiences and to share data and understanding with them. A copy of Klein's unpublished report is appended hereto.

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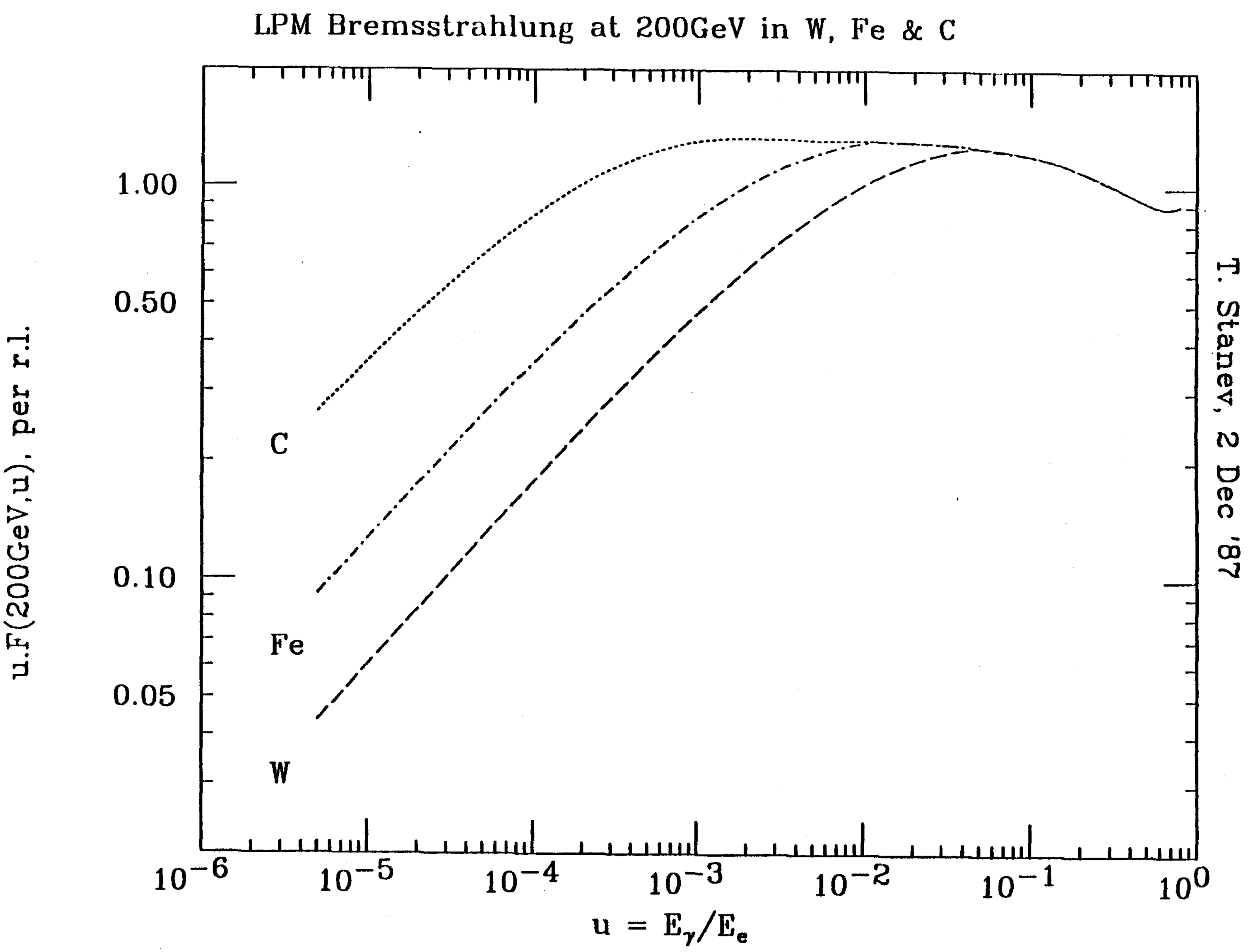

Figure 1. Stanev theoretical calculation of LPM effect (Migdal formula) for 200 GeV electrons incident on radiators of C, Fe, and W. Very thin radiators assumed, i.e. no multiple radiation from each electron

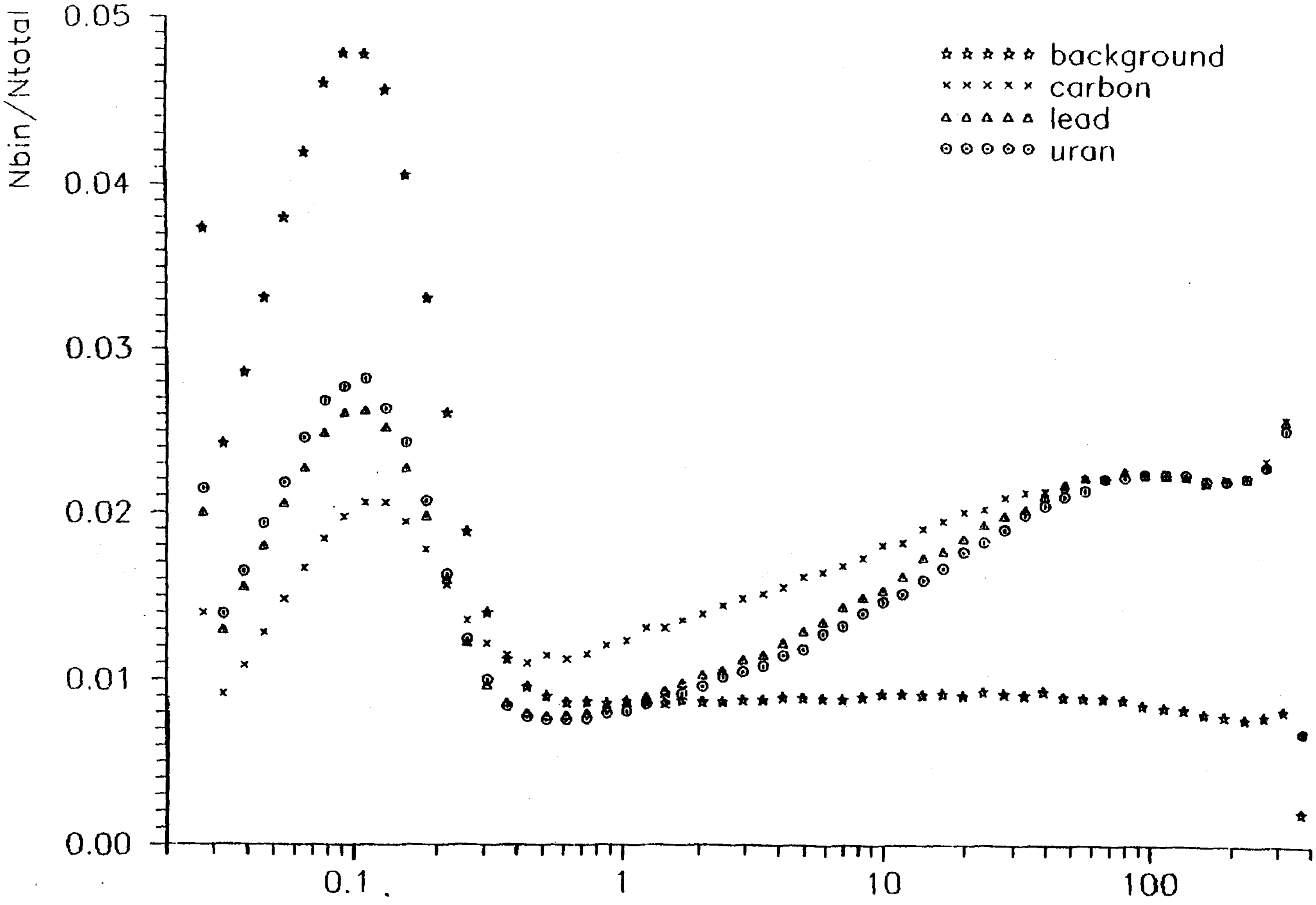

Figure 2. Lódź Monte Carlo; 350 GeV electrons incident on 0.05 r.l. Be (background), on 0.05 r.l. Be + 0.10 r.l. C, on 0.05 r.l. Be + 0.10 r.l. Pb, and on 0.05 r.l. Be+ 0.10 r.l. U. Each run contains 10^6 electrons. Synchrotron radiation from 0.5T over 2 m included. The distributions are normalized to one electron.

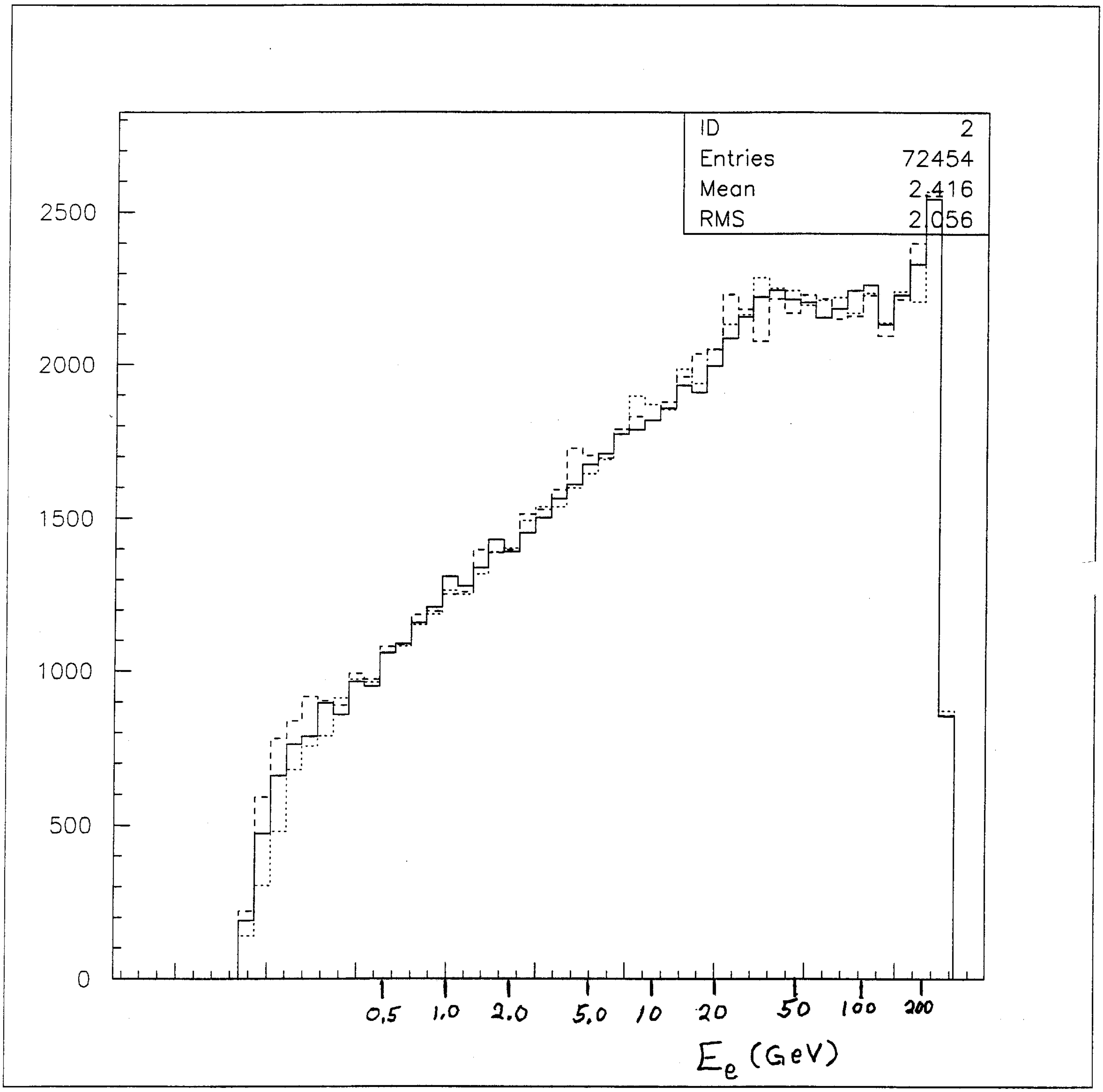

Figure 3. Michigan Monte Carlo; 250 GeV electrons incident on 0.05 r.l. Be + 0.10 r.l. C; 10^5 electrons each run. Solid line: Migdal formula, dashed line: Bethe-Heitler; dotted line: Landau-Pomeranchuk approximation. The abscissa scale is logarithmic. Synchrotron radiation not included.

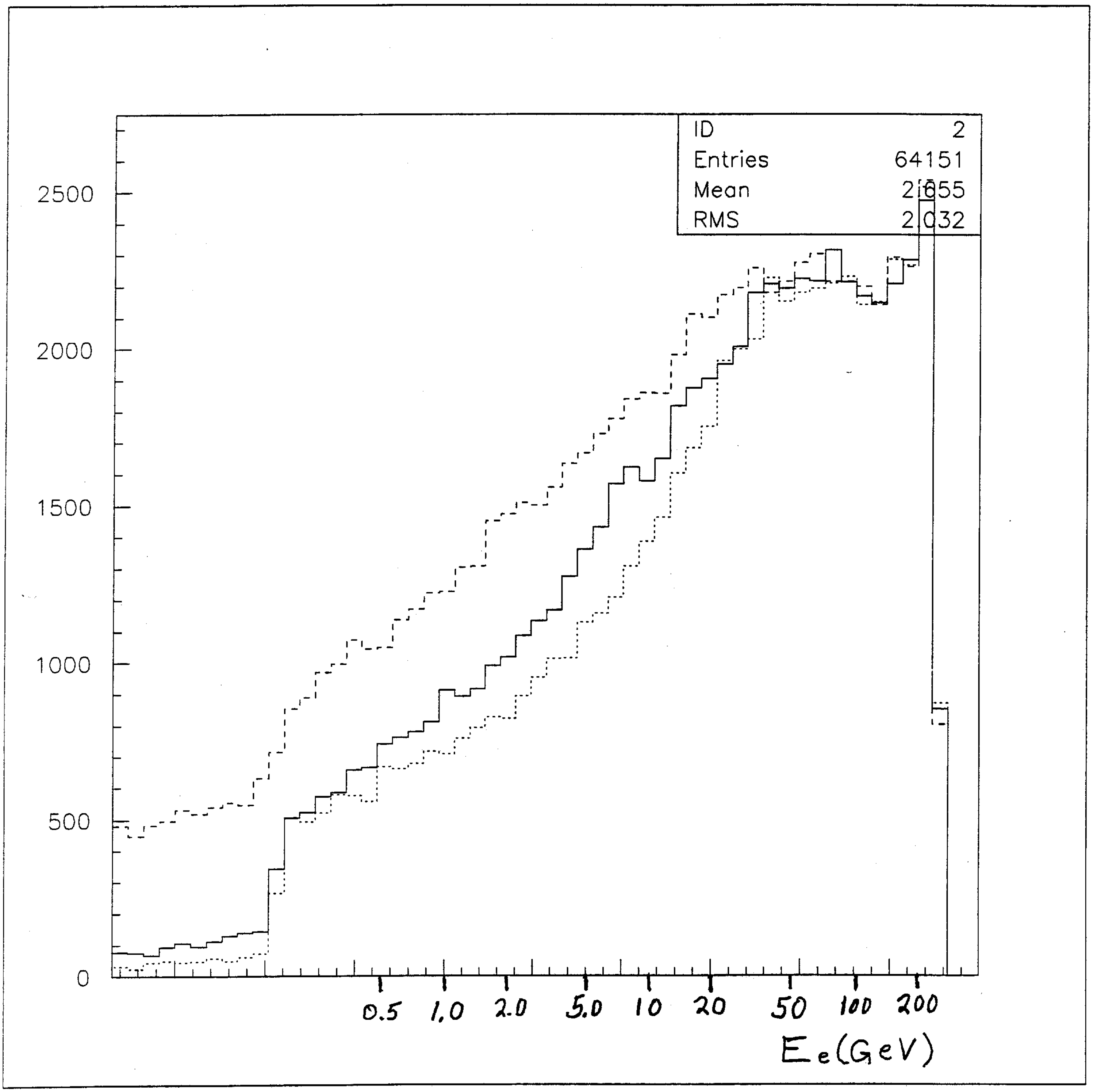

Figure 4. Michigan Monte Carlo; 250 GeV electrons incident on 0.05 r.l. Be + 0.10 r.l. W; 10^5 electrons each run. Solid line: Migdal formula, dashed line: Bethe-Heitler, dotted line: Landau-Pomeranchuk approximation. The abscissa scale is logarithmic. Synhcrotron radiation not included.

ELECTRONICS SCHEMATIC

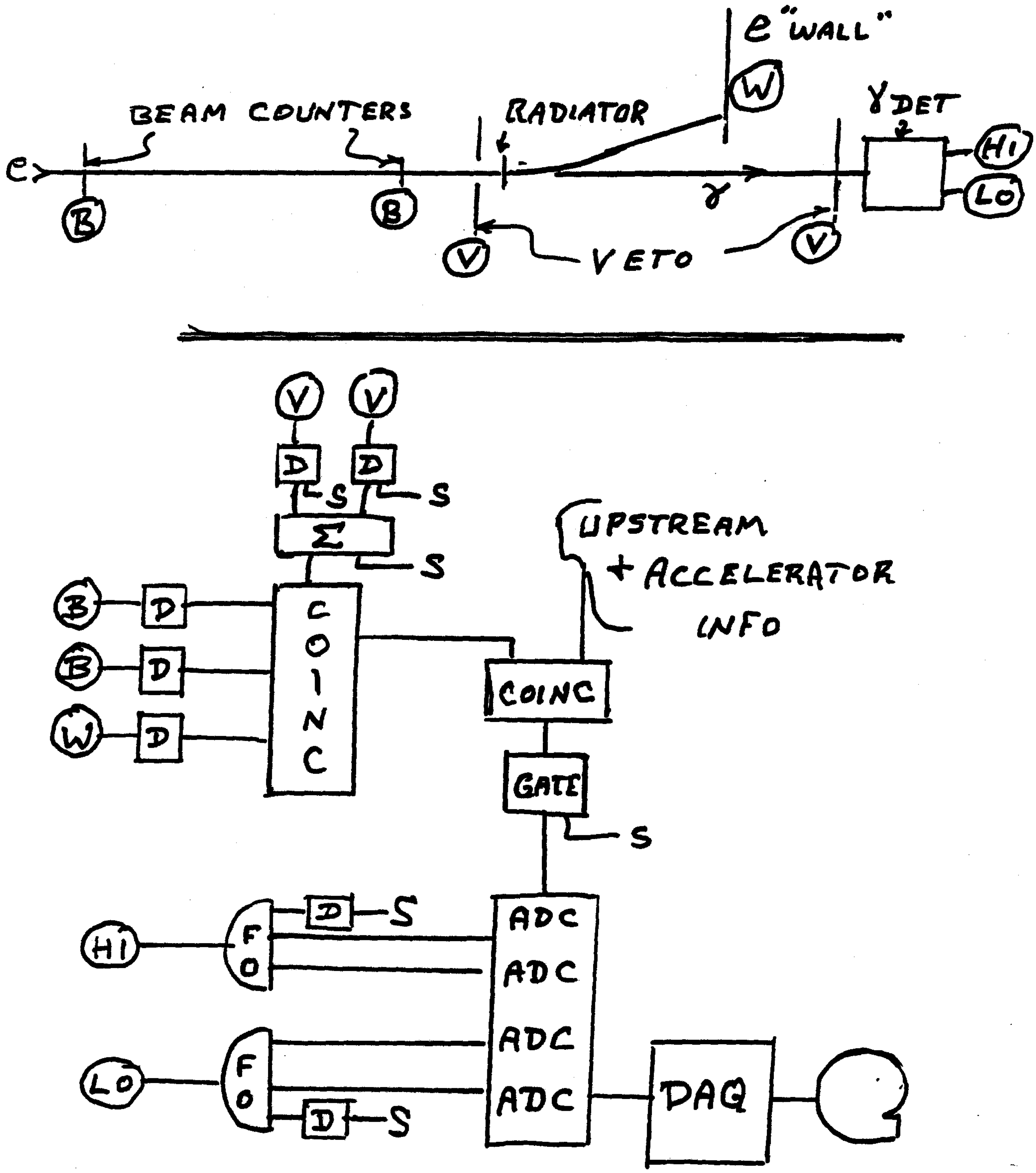

Figure 5.

Table 1

The LPM Effect Some useful numbers

The LPM effect reduces Bremsstrahlung for $E_\gamma < E_T$, $\quad E_T = E_e^2/E_{LPM}$;
The initial electron energy is E_e and $E_{LPM} = 7.6X_0$ (TeV);
The radiation length X_0 is in cm.

Element	X_0 (cm)	E_{LPM} (TeV)	E_e=25 GeV E_T	E_e=250 GeV E_T	E_e=350 GeV E_T
Be	35.3	268	2.33 MeV	233 MeV	457 MeV
C	18.8	143	4.37 MeV	437 MeV	857 MeV
Fe	1.76	13.4	46.6 MeV	4.66 GeV	9.14 GeV
Pb	0.56	4.26	147 MeV	14.7 GeV	28.8 GeV
U	0.32	2.43	257 MeV	25.7 GeV	50.4 GeV

The reduction in gamma flux $\phi = \frac{dN_\gamma}{dE}$ below E_T relative to the Bethe-Heitler spectrum (which is approximately flat in $E_\gamma \frac{dN_\gamma}{dE}$) for a given fraction below E_T is seen from the following representative numbers:

$\frac{E_\gamma}{E_T}$	60%	10%	1.0%
$\frac{\phi_{LPM}}{\phi_{BH}}$	$\approx$ 97%	$\approx$ 70%	$\approx$ 30%

As an example, $E_T(C) = 0.017 E_T(U)$. At 0.60 $E_T(C)$, the flux from U has fallen to about 31% of the flux from C (normalized at high energy and for very thin radiators). This occurs at $\approx$2.6 MeV for 25 GeV electrons and at $\approx$500 MeV for 350 GeV electrons.

Table II

Comparison of Approximate and Exact Calculations

Approximate (Landau-Pomeranchuk) refs. 1, 2, 3; ϕ_{L-P}.

Exact (Migdal) refs. 4, 5, 6; ϕ_m.

Gamma fluxes ϕ for Carbon (C) and Tungsten (W) radiators.

E_γ	E_e=350 GeV $(\phi_m/\phi_{L-P})\%$		E_e=250 Gev $(\phi_m/\phi_{L-P})\%$	
(GeV)	C	W	C	W
1	5.6	3.8	3.4	3.9
2	3.5	4.0	1.0	4.5
5	-0.8	5.1	-1.1	6.3
10	-1.1	6.6	-1.4	7.9
20	-1.4	8.3	-1.5	8.8
50	-1.6	9.1	-1.6	6.4
80	-1.6	7.7	-1.5	3.2

These flux ratios include synchrotron radiation effects and are based on Monte Carlo runs of 10^6 electrons, each run.

Table III

The LPM Magnetic Effect

From Spencer Klein (private communication): the LPM magnetic effect sets in for gamma energies, E given by:

$$E_\gamma \leq 2E_{e\gamma}\,\frac{B}{B_c},\quad \text{where } B_c = 4.4\times 10^{13}\text{ Gauss}$$

For $E_e = 350\text{GeV}, \gamma = 0.684\times 10^6$, and for $B = 20,000$ Gauss, $E_\gamma \leq 213MeV$.

Table IV

Prep List

2 NIM Bins + Pwr

2 HV(PMT) Supplies

1 COW

1 CAMAC Crate

15 <u>OLD</u> NIM Modules

8 <u>OLD</u> CAMAC Modules

1 Scope; Tek'x 475 (or later; e.g. 2265)

(some could come form U.M. e.g. 2249 ADCs)

- Minimal computer; data logging system coupled to DECnet, and storage device.
- Interface to FNAL controls/timing.

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A MEASUREMENT OF THE LPM EFFECT*

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We have performed an experiment to measure accurately the Landau-Pomeranchuk-Migdal (LPM) effect in the production of 5 to 500 MeV photons due to bremsstrahlung of 8 and 25 GeV electron beams traversing thin (2 to 6% X_0) targets of varying densities. Our measurements confirm that the LPM effect exists and that the Migdal calculations are accurate. We see that, for thin targets, LPM suppression disappears leaving a Bethe-Heitler spectrum, as predicted by theory. For intermediate target thicknesses, we lack an acceptable theory, but have measured energy spectra for targets of differing thickness.

We have also measured the production rate of 500 keV to 5 MeV photons at the same electron energies, to study dielectric suppression. We see qualitative agreement with the theory of Ter-Mikaelian; more work is needed before we can make quantitative comparisons.

I. INTRODUCTION

In the early 1950s, a group of Russian theorists led by Landau, Pomeranchuk, Migdal, and Feinberg realized that because of the low longitudinal momentum transfer between the nucleus and the electron, bremsstrahlung is not really a point interaction, but occurs over a finite formation zone. While the electron traverses this formation zone, external influences can perturb the electron and suppress or enhance the photon emission, causing the traditional Bethe-Heitler (BH) formulae to fail. A well known example of this is crystal channeling, where photon emission by bremsstrahlung can be enhanced. Another example, discussed below, is the suppression of low-energy photons when the photon energy becomes comparable to the electron gamma times the plasma frequency of the media. A third example is the suppression of bremsstrahlung when multiple scattering disrupts the electron trajectory; this is known as the Landau-Pomeranchuk- Migdal (LPM) effect, after its discoverers.

Initially, Landau and Pomeranchuk used semiclassical arguments to determine that multiple scattering can change the $1/\omega_\gamma$ photon spectrum to $1/\sqrt{\omega_\gamma}$ [1]. Migdal later used scattering theory to quantify the effect more fully [2].

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Ithaca, NY, August 10-15, 1993

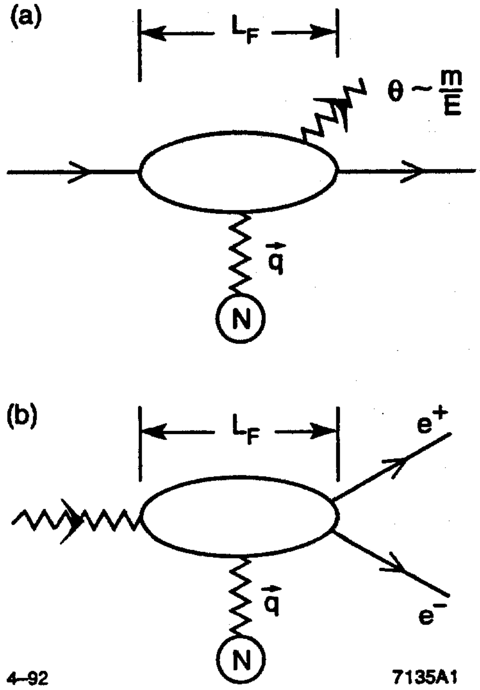

FIG. 1. Diagrams for (a) bremsstrahlung and (b) pair production, showing the formation zone.

Because Migdal's derivation is mathematically involved, we will present here a semiclassical derivation of Feinberg and Pomeranchuk [3].

The classical diagram for bremsstrahlung is presented in Fig. 1. An electron emits a photon, conserving momentum by exchanging a virtual photon with a nearby nucleus. The transverse momentum exchanged with the nucleus is up to the mass of the electron, m. However, the longitudinal momentum transfer is much smaller,

$$q_{\|} = p_e - p_e' - k = \sqrt{E_e^2 - m^2} - \sqrt{E_e'^2 - m^2} - E_\gamma,$$

where p_e, p_e', E_e, and E_e' are the electron momentum and energy before and after the interaction, respectively, and E_γ is the photon energy. For high-energy electrons this simplifies to

$$q_{\|} \sim \frac{m^2 E_\gamma}{2E_e(E_e - E_\gamma)} \sim \frac{E_\gamma}{2\gamma^2},$$

where γ is E_e/m, and the latter relationship only holds for $E_\gamma \ll E_e$.

This momentum transfer can be very small. For example, for a 25 GeV electron emitting a 100 MeV photon, $q_{\|}$ is only 0.02 eV/c. Then, by the uncertainty principle, the virtual photon exchange distance is finite, $c\gamma^2/\omega_\gamma$. For a 100 MeV photon from a 25 GeV electron, the formation zone is 10μm long.

The LPM effect comes into play when one considers that the electron must be undisturbed while it traverses this distance. One factor that can disturb the electron, and suppress the bremsstrahlung, is multiple Coulomb scattering. If the electron multiple scatters by an angle θ_{MS}, greater than the emission angle of the bremsstrahlung photon, $\theta_B \sim m/E_e = 1/\gamma$, then the bremsstrahlung is suppressed.

One parameterization for multiple scattering is

$$\overline{\theta}_{MS}^2 = (\frac{E_s}{E_e})^2 \frac{l}{X_0},$$

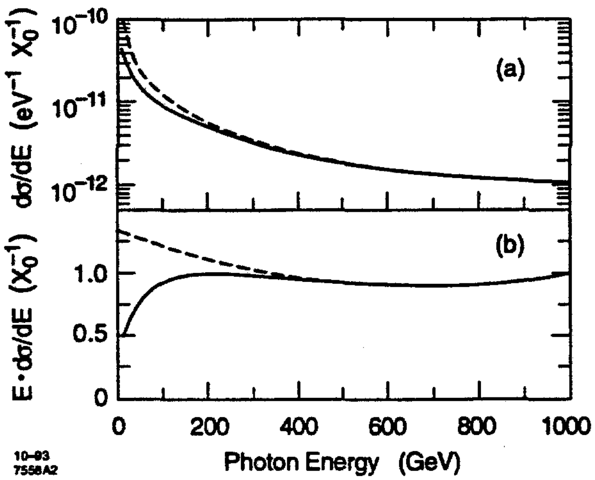

FIG. 2. (a) $d\sigma/dE_\gamma$ and (b) $E_\gamma \times d\sigma/dE_\gamma$ for bremsstrahlung from 1 TeV electrons in uranium for the BH and LPM formulae.

where E_s is the characteristic energy, $\sqrt{4\pi/\alpha} \cdot m_e = 21$ MeV, l is the target thickness, and X_0 is the radiation length. The above formula is inaccurate for thin media, where single large scatters can contribute significantly to the total scattering; Migdal's analysis considers this in more detail. The LPM effect becomes important when θ_{MS} is larger than θ_B. This occurs for $E_s/E_e\sqrt{x/X_0} > m/E_e$. Some algebra shows that for a given electron energy, suppression becomes significant for photon energies below a certain value, given by

$$x = \frac{E_\gamma}{E_e} < \frac{E_e}{E_{LPM}},$$

where all of the constants have been lumped into E_{LPM}, given by $E_{LPM}(\mathrm{eV}) = m^4 X_0/c\hbar E_s^2 = 7.6 \times 10^{12} X_0(\mathrm{cm})$ about 2.6 TeV in uranium and 4.2 TeV in lead. For example, suppression becomes significant for 250 MeV photons from a 25 GeV electron in uranium.

Finding the magnitude of the suppression is more involved. When $E_\gamma \ll E_e$, the photon dN/dE$\sim 1/\sqrt{E_\gamma}$, in contrast to the $1/E_\gamma$ Bethe-Heitler spectrum. At larger photon energies, a more fully quantum-mechanical analysis is needed. Migdal used the densities of wave states and scattering theory to calculate cross sections for all photon energies. Unfortunately, his formulae are recursive and difficult to use. The calculations for E-146 use a noniterative approximation developed by Stanev and collaborators [4]. The magnitude of the LPM effect for 1 TeV electrons in uranium ($E_e \sim 1/2\ E_{LPM}$) is shown in Fig. 2.

John Bell has pointed out that the LPM effect conflicts with classical electromagnetism by requiring that total radiation from the electron decrease as the electron energy increases [5]. Bell repeated and confirmed Migdals calculations. He argued that the discrepancy between the classical and quantum mechanical calculations is resolved by an increased emission of high-energy photons, where the classical formula is clearly inappropriate. Although doubts have been raised about Bell's calculations [6], his comments demonstrate that the ideas underlying the calculations are of fundamental interest.

An analogous effect occurs for pair creation by a high-energy photon. As Fig. 1 shows, the two processes are closely related. In pair creation, the LPM energy threshold is determined by the lepton with the lower energy. Because of this, suppression of pair creation begins at much higher energies than does bremsstrahlung suppression.

II. THE LONGITUDINAL DENSITY EFFECT AND MAGNETIC SUPPRESSION

Although the LPM effect reduces the divergence of the low-energy-photon production cross section, it does not eliminate it, since dN/dE$_\gamma$ still grows as $E_\gamma^{-1/2}$. Another effect, which occurs at very low photon energies, removes the divergence. At low enough photon energies, the phase shift due to the effect of the medium on the photon, taken over the formation length, can become significant, and introduce a destructive interference. This effect is called the longitudinal density effect. In particle language, this phase shift occurs because the emitted bremsstrahlung photons undergo coherent forward Compton scattering off the electrons in the medium.

In classical electromagnetic language, the phase shift is due to the dielectric effect of the medium. The contributions to the photon amplitude, $\exp(i(k\cdot x-\omega t))$, from different parts of the electron path through the formation zone can interfere, and photon emission is suppressed [7]. This effect is related to the dE/dx (transverse) density effect discussed by Fermi. The density effect is significant for photon energies less than $\gamma\omega_p$, where ω_p is the plasma frequency. For a given material, this occurs at a fixed E_γ/E_e, and the suppression factor is [8]

$$\frac{\sigma_{density}}{\sigma_{no-density}}=(1+\frac{nr_e\lambda_e^2E_e^2}{\pi E_\gamma^2})^{-1},$$

where n is the electron density, r_e is the classical electron radius, and λ_e is the electron Compton wavelength. The density effect becomes important for $x=E_\gamma/E_e<10^{-4}$ in lead, and 5.5×10^{-5} in carbon. Below these energies, $dN/dE_\gamma\sim E_\gamma{}^2$, removing the divergence.

In addition to disruption due to multiple scattering and dielectric effects, it is also possible for a magnetic field to suppress the bremsstrahlung. Magnetic suppression begins at an energy at which the bending due to the magnetic field, taken over the formation zone length, is larger than the bremsstrahlung emission angle $1/\gamma$. This happens for photon energy fractions $x<2\gamma B/B_c$ where B_c is the critical magnetic field, $m_e^2c^3/e\hbar=4.4\times10^{13}$ Gauss [9].

III. IMPLICATIONS OF THE LPM EFFECT

The LPM effect is relevant in a wide variety of physics applications. One of the most obvious applications is in calorimeters designed to study TeV particles, for example at TeV Linear Collider (TLC), Large Hadron Collider (LHC), or Next Linear Collider (NLC). All of these colliders can produce multi-TeV electrons, for which the LPM effect is large. Figure 2 shows one example, comparing the LPM and BH cross sections for a 1 TeV electron in uranium. The area under the energy-weighted cross-section curve is inversely proportional to the radiation length; it increases by about 5% due to the LPM correction. However, the major change is an increase in granularity of the showers, due to suppression of low-energy photons which would fill out the showers. This makes electromagnetic showers appear more like hadronic showers, reducing electron-hadron separation. For example, electrons may mimic pions in tau decays. Unfortunately, no calorimeter design studies include the LPM effect; the effect is omitted from both EGS and GEANT, although suppression due to dielectric effects is included in GEANT, but labeled as the Migdal effect. Analogous effects can occur in beamstrahlung [10].

The effects of LPM suppression on cosmic ray air showers have been discussed by many authors [11]. In exceedingly high-energy (above 10^{18} eV) photon-induced air showers, the LPM effect increases the graininess of the shower, and changes the shower particle density distribution used in determining total shower energy. Current air shower detectors are insensitive to this effect, but future detectors will be more sensitive. Another potential impact occurs for electromagnetic showers from high-energy ν_e as might be produced by active galactic nuclei, and be observed by *DUMAND* [12].

The electronic LPM effect has a number of analogs in nuclear physics involving quarks and gluons moving through matter. Just as the original LPM effect predicts that photon emission from electrons traveling through dense charged matter can be suppressed, the nuclear analog predicts that gluon emission from quarks and gluons traveling through dense nuclear matter will be suppressed. Although the nuclear length scales are small, the elastic-scattering cross section is large, so the suppression is large. Brodsky and Hoyer have recently derived limits on color dE/dx, using formalisms similar to those used in LPM papers [13]. However, all analyses of QCD analogs are complicated by the strong-coupling nature of QCD, which makes interpretation of the data less than straightforward.

Another system in which LPM-type suppression appears is stellar interiors. Because the particles are nonrelativistic, it is easier to think temporally, comparing the Heisenberg emission times, calculated via the energy transfer with the average time between collisions. Because the density is very high, collisions are very frequent, leading to suppression of particle emission by nuclear bremsstrahlung. Raffelt and Seckel have shown that because the nucleon collision rate Γ_{coll} far exceeds the oscillation frequency of neutrino or axion radiation [14], production of these exotic particles is suppressed, and a number of existing limits will need to be reexamined.

IV. PREVIOUS EXPERIMENTS

A number of previous experiments have attempted to study the LPM effect and dielectric suppression. Except for a 1975 Soviet experiment, all of the LPM studies have used cosmic rays.

Most of the cosmic ray experiments were performed during the 1950s [15], with a few more recent results [16]. Most have looked at the depth of pair conversion in a medium for high-energy photons. They qualitatively confirmed the LPM effect, but with very limited statistics.

An experiment at Serpukhov [17] using 40 GeV electrons, was troubled by limited statistics, large systematic errors, and muon background, and so only produced a qualitative agreement with the LPM theory. The electrons transited a thin target, were bent by a magnet, and disposed of. A NaI crystal detected 20–80 MeV bremsstrahlung photons. The experiment suffered from large backgrounds, including bremsstrahlung in the air around the target and in the defining scintillation counters, debris from electrons hitting beam pipe walls, and synchrotron radiation.

Most of the experiments that have reported results on dielectric suppression were done by an Armenian group using electrons in the 1 GeV range to generate $\sim$ 100 keV photons. The experiments were optimized for transition radiation, but they have reported some results with solid targets, albeit of mixed quality [18].

Our experiment followed the general model of the Soviet LPM experiment but differed in almost all the particulars, to avoid the backgrounds that caused them trouble, and to measure several additional facets of the LPM effect.

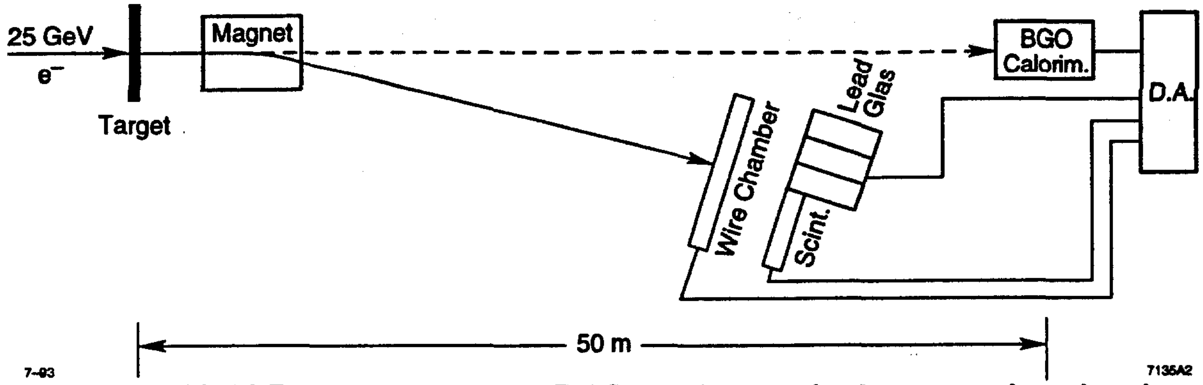

FIG. 3. The layout of SLAC-E-146. Electrons entering End Station A traversed a thin target and were bent downward by a bending magnet into a set of wire chambers and a lead glass block array. Bremsstrahlung photons emitted in the target continued downstream into a BGO calorimeter.

V. EXPERIMENTAL APPARATUS

Figure 3 shows a diagram of our experiment [19]. A 25 GeV electron beam enters Stanford Linear Accelerator Center (SLAC) End Station A and passes through a thin target. The beam is then bent downward by a 3.25 T-m dipole magnet, through six wire chamber planes which measure its momentum, and into an array of lead glass blocks which accurately count electrons. Produced photons continue downstream 50 meters into a BGO calorimeter array. To minimize backgrounds, the electron path visible to the calorimeter and the photon flight path are kept in vacuum.

A. Targets

The targets used are shown in Table 1. We used materials of a variety of densities and atomic numbers. The thicknesses chosen were a compromise between minimizing multiple photon emission from a single electron traversing the target, and maximizing the bulk LPM emission compared to edge effects. For most of the target materials, we used two targets with differing thicknesses. This allows a check on thickness-dependent effects, and for the possibility of removing edge effects by spectrum subtraction.

The targets were held in a seven-position target holder. During data acquisition, we cycled through the targets, typically changing targets every two hours. One position in the holder was always kept empty to allow us to take no-target background data. Another held a 1-cm-square silicon diode. The diode was sensitive to minimum ionizing particles, and was used periodically to measure the beam size and position.

B. Calorimeter

The BGO calorimeter, built in 1984 [21], is composed of 45 crystals in a 7 by 7 array with missing corners; each crystal measures 2 cm square by 20 cm (18 X_0) deep. This segmentation provides excellent position resolution, which is useful in separating synchrotron radiation from bremsstrahlung photons. The calorimeter response was studied previously with 40–100 MeV electrons at the Monterey Naval Postgraduate School Linac and with 1–8 GeV electrons

TABLE I. Targets Used in E-146. The gold targets were intended mainly to allow us to study very thin targets. The LPM energy is the highest energy for which LPM suppression is significant in the given target material.

Target Material	Z	X_0 (cm)	Thickness (X_0)	LPM Energy (MeV)
Carbon	6	18.8	2%, 6%	4.4
Aluminum	13	8.9	3%, 6%	9.2
Iron	26	1.8	3%, 6%	47
Tungsten	74	0.35	2%, 6%	235
Gold	79	0.34	0.1%, 1%, 6%	240
Lead	82	0.56	2%	147
Uranium	92	0.32	3%, 5%	265
Blank	-	-	-	-

at SLAC. These data were used to estimate the calorimeter nonlinearity (2%). Since BGO light output is known to change with temperature, we monitored the temperature throughout the experiment, and will use this data to correct for temperature drifts.

For this experiment, we used a number of methods to recalibrate the calorimeter, to obtain both an absolute energy calibration and a crystal-to-crystal intercalibration. The primary tools for measuring the relative gain were cosmic-ray muons, selected by a scintillator paddle trigger. Nearly vertical cosmic rays were selected, and the gain in each crystal was adjusted to produce equal signals.

The primary method for obtaining the absolute calorimeter gain was to run 400 and 500 MeV electron beams directly into the calorimeter. This calibration can be checked by comparing the electron energy loss, measured by the wire chamber, with the energy measured in the calorimeter. Because of the steeply falling photon spectrum and the non-Gaussian errors in the momentum measurement, this is a difficult measurement, but is useful as a check.

At very low energies, we took calibration data with a ^{60}Co source, which emits photons in pairs, with energies of 1.173 and 1.333 MeV. A scintillator triggered on one of the photons, providing an unbiased trigger for the other photon to interact in the BGO.

At this point, we estimate that the calorimeter calibration is accurate to 10%. In the future, this error should be roughly halved.

C. Spectrometer

The 18D72 bending magnet and the wire chambers formed a spectrometer which measured the momentum of the outgoing electrons. The 3.25 T-m field bent 25 GeV electrons downwards by 39 mrad, or 58 cm at the wire chambers, which were 15 meters downstream. The six wire chamber planes had a 2 mm wire spacing. Four of the planes provided y (momentum) information and the other two planes were angled to provide side to side positional information. With the 2 mm wire spacing and the 15 meter lever arm, we achieved a 100 MeV energy resolution, adequate to suppress many types of backgrounds, and to help calibrate the calorimeter.

D. Beam

The experiment required a beam intensity of about 1 electron per pulse. Because it would be very uneconomical to run the SLAC linac to produce a single electron per pulse, we devised a method to run parasitically during SLC/SLD operations, by using the particles that SLC throws away [20].

To do this, we took advantage of the roughly 10% of the SLC beam that, during normal operations, is scraped away by the collimators in sectors 29 and 30 of the SLAC linac. Because the collimators are only 2.2 X_0 thick, a usable flux of high-energy photons emerges from the back and sides of the collimator. A small fraction of these photons travel down the beampipe, past the magnets that bend the electrons and positrons into the SLC arcs, and into the beam switchyard. There, we placed a 0.7-radiation-length target to convert these photons into e^+e^- pairs. A fraction of the produced electrons were captured by the A-line optics and transported into the end station.

Although it sounds like a Rube Goldberg contraption, this process worked extremely well, and the beam size, divergence, and yield matched our simulations. At 8 and 25 GeV, the beam intensity was in the 1–100 electrons/pulse range. To minimize the spot size in the calorimeter, the beam optics were adjusted to produce a virtual focus at the calorimeter; photon spot sizes there were typically a few mm in diameter. The beam spot was stable enough and small enough that beam motion was not a problem.

VI. DATA ANALYSIS AND RESULTS

This analysis will only consider events containing a single electron. While multiple electron events can be used to study systematic effects and improve the statistics, their analysis is more involved and will not be discussed here. Single electron events were selected by requiring that the energy deposition in the lead glass blocks match that for a single electron, with no energy deposited in the veto counters which detected lower energy electrons. The photon energy was found by summing the energies of hit BGO crystals using a cluster-finding algorithm. The cluster finding reduced the noise level by eliminating random hits. The energies were histogrammed logarithmically using 25 bins per decade of energy, so that each bin had width $\Delta E \sim 10\% E$. The logarithmic binning was chosen because a $1/E_\gamma$ BH spectrum will have an equal number of events in each bin, simplifying the statistical analysis.

A. Backgrounds and Monte Carlo

The backgrounds to the LPM measurement were small. The major background-related correction is for multi-photon pileup, when a single electron emits two bremsstrahlung photons while traversing the target. This correction is accounted for in the Monte Carlo simulation.

The Monte Carlo tracked electrons through the material in small steps, allowing for the possibility of bremsstrahlung in each step. It used the formalism developed by Stanev and collaborators [4] to avoid the recursion in the formulas developed by Migdal. However, numerical tables of Φ and G given by Migdal were used, rather than the series given by Stanev. The longitudinal density effect was included by a simple multiplicative factor [8]. Either the LPM or longitudinal density effects could be turned off as needed. By choice, and for consistency, our BH Monte Carlo results were obtained by turning off the LPM effect, but otherwise using Migdal's formulae, rather than newer formulae that include some subtle corrections. Because we are in the region of complete nuclear screening, these corrections are small.

Produced photons can either exit the target or be lost by Compton scattering or pair conversion, according to tabulated probabilities [22]. Because of the low probabilities, large production angles, and small sensitive solid angles, bremsstrahlung from secondary electrons from pair conversion have a negligible effect on our data. Finally, although it is a small effect, our Monte Carlo includes a simple model of the calorimeter resolution.

Background sources included synchrotron radiation, transition radiation, and photonuclear interactions. Synchrotron radiation from both the final A-line bending magnet and our spectrometer magnet were considered. The good photon positional resolution provided by the BGO calorimeter allowed us to identify most synchrotron radiation by positional cuts. Because of the large fringe field of the spectrometer magnet, the electron bend began very gradually, and synchrotron radiation reaching the calorimeter came from low field regions. Because of this, synchrotron radiation hitting the center calorimeter crystal came from regions with a maximum critical energy of 100 keV.

Transition radiation as electrons enter and leave the target, is also very small, amounting to an average of 14 keV per electron, with the photon spectrum extending only up to $\gamma\omega_p$, the same energies at which the longitudinal density effect occurs [23]. So, this background is negligible above 5 MeV.

The photonuclear cross section is a small fraction of the bremsstrahlung cross section. In addition, the chance of a photonuclear interaction mimicking bremsstrahlung in our detector is very small, so photonuclear interactions should have negligible effect on our data.

The non-target-related backgrounds were checked by taking data with an empty target holder. This showed that our backgrounds were indeed very low, typically 0.1% of a photon per electron. Compared with the 20–60% per electron chance of a bremsstrahlung photon, it is clear that the non-target-related backgrounds are indeed small.

Most possible target-related backgrounds should distribute photons all over the calorimeter, in contrast to bremsstrahlung, which should be concentrated in the center. The observed paucity of hits away from the central region indicates that target related backgrounds are also small.

B. Results

We present our results in comparison with two Monte Carlo calculations, one for the BH spectrum and the other including the LPM and longitudinal density effects. Figure 4 compares the result of our calculations with the data for 2% X_0 and 6% carbon radiators. The dashed line on the 2% plot shows the raw BH cross section; multiphoton pileup is a large effect even for the relatively thin targets. The two spectra differ below about 10 MeV; the data shows a downturn which matches the LPM spectrum. In this and successive plots, we have adjusted the normalization to match the data. For 2% carbon, this was a 6% adjustment; for the other samples the normalization adjustment is between 3% and 7%; this is within the range of our systematic errors.

The LPM effect is much more significant in denser, high Z targets. Figure 5 shows the bremsstrahlung spectrum for 25 GeV electrons traversing 3% and 5% uranium targets. The spectrum agrees well with the LPM Monte Carlo

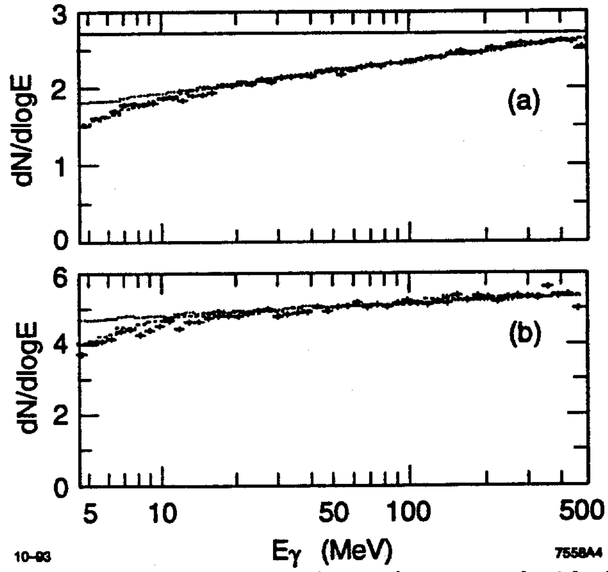

FIG. 4. The bremsstrahlung spectrum, $d\sigma/d\log(E)$ data (crosses), compared with the LPM (dashed histogram) and BH (dotted histogram) Monte Carlos, for (a) 2% and (b) 6% X_0-thick radiators of carbon. The cross section units are photons per bin (with 25 bins per decade) per 1000 electrons. The solid line in (a) shows the BH cross section neglecting multi-photon effects.

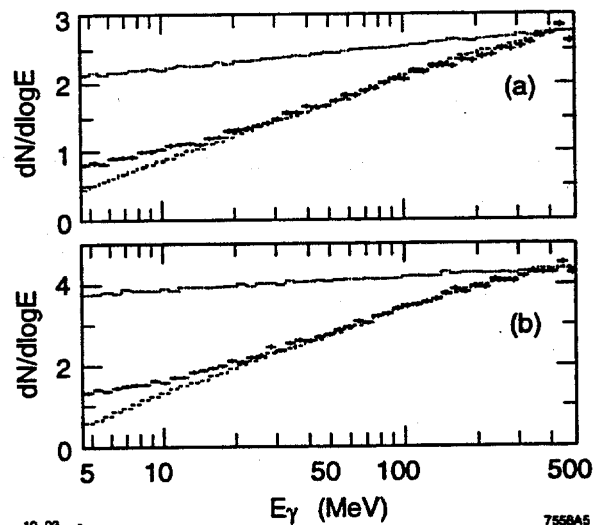

FIG. 5. The bremsstrahlung photon spectrum for 25 GeV electrons traversing (a) 3% and (b) 5% uranium radiators. The dotted histograms are the BH Monte Carlo, the dashed histograms the LPM Monte Carlo, and the crosses are data.

down to about 25 MeV, while the BH curve is clearly ruled out. Below 25 MeV, the data is significantly higher than the Monte Carlo. This is because of edge effects as the electron enters and leaves the target.

C. Thin Targets and Edge Effects

If an electron radiates near the target edge, the formation zone can extend outside of the target, where there is no multiple scattering. Then, less LPM suppression occurs.

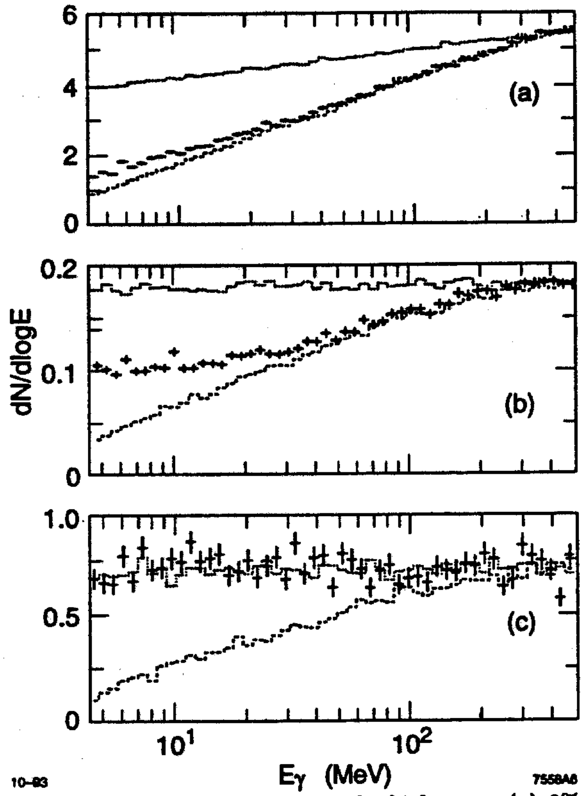

FIG. 6. The bremsstrahlung spectra for three gold targets with thicknesses (a) 6% X_0, (b) 1% X_0, and (c) 0.1% X_0. The dotted histograms are the BH Monte Carlo, the dashed histograms the LPM Monte Carlo, and the crosses are data. As the target becomes thin compared to the formation zone length, LPM suppression disappears and the BH spectrum reappears.

For very thin targets, where the multiple scattering angle, taken over the entire target thickness is less than $1/\gamma$, LPM suppression should not be present, and a BH emission spectrum should be seen. For thicker targets, one might expect an 'edge effect' to account for scattering near the material boundaries, with the bulk material retaining the LPM spectral emission.

Because the formation zone length scales as E_e^2/E_γ, these effects should be photon energy dependent. However, it should also be noted that the formation zone has a maximum length limited by the longitudinal density effect.

The absence of LPM suppression in thin targets and the appearance of edge effects can be explored by comparing spectra from three gold targets, one quite a bit thicker than the formation zone length at these energies (6% X_0, or 200 μm), one comparable to the formation zone length at 30 MeV (1% X_0, or 30 μm), and one much thinner than the formation zone length over the 5–500 MeV range (0.1% X_0, or 3 μm).The spectra for these targets are shown in Fig. 6.

Gol'dman [24] studied this problem theoretically; unfortunately he did not present his results in closed form. Later, Ternovskii [25] extended his treatment, and gave clear formulae. Both authors described a sort of transition radiation to mark the change in the electron's forward velocity, as it changes from a straight trajectory to being scattered by collisions with the atoms in the target media. This is intended to be analogous to the more traditional transition radiation. Unfortunately, Ternovskii's formulae are unphysical, and predict transition radiation far in excess of the discrepancies shown in the data.

We can partially bypass these edge effects and measure the bulk LPM effect by subtracting the spectra of two targets of the same material but differing thickness. Figure 6 shows the difference between the 5% and 3% uranium targ

TABLE II. Summary of Systematic Errors in the E-146 LPM Measurement. The effects of the errors are given in terms of their affects on the absolute and relative cross section measurements. The absolute cross section measurement is taken at 500 MeV, while the relative σ is the amount that the cross section can change at other energies, relative to the 500 MeV point. The calorimeter calibration and cluster finding entries show the amount that the allowed energy shifts could affect the cross section measurement for the 5% uranium target. Other targets will have similar or smaller shifts. For conservatism, and since several of these errors are clearly non-Gaussian, the errors are added linearly here.

Source	σ(500 MeV)	σ(Relative)
Backgrounds		1%
Calorimeter Calibration (10%)	2%	2.5%
Cluster Finding (10%)		2.5%
Target Thickness	2%	
Target Density		2%
e^- flux	3%	
Monte Carlo	1%	3%
Subtraction		8%
Sum	8%	19%
Migdal Formulae	5%	5%

spectra, properly normalized to account for the number of electrons impacting each target. With this subtraction, the data agrees well with the LPM Monte Carlo down to 15 MeV; below 15 MeV the data is slightly higher than the Monte Carlo. The BH prediction is clearly excluded.

The disagreement with the LPM Monte Carlo is due to an offset introduced by the subtraction procedure. While the Monte Carlo accounts for multiphoton emission, it does not include the additional multiphoton emission due to the transition radiation. Thus, the subtraction procedure removes the transition radiation, but undercompensates for the multiphoton emission, and predicts a smaller cross section than the data. In the future, we plan to fit the edge effects numerically and include them in the Monte Carlo. For the present analysis, it is difficult to predict the magnitude of the correction, but it is not inconsistent with the currently observed discrepancy.

D. Systematic Errors

The major systematic errors come from backgrounds, uncertainties in the electron flux, target thickness and density, Monte Carlo accuracy, calorimeter calibration, and calorimeter cluster finding. Our preliminary estimates of these systematic errors are summarized in Table 2.

We have divided the cross section errors into two parts: absolute and relative. The absolute part applies to a measurement of the cross section at 500 MeV, the energy at which we calibrated the calorimeter with an electron beam. The relative part refers to how much the cross section changes across the 5 to 500 MeV range. So, the relative cross section is relevant when considering the shape of the curve.

As previously discussed, the major backgrounds are synchrotron radiation, transition radiation, and nuclear interactions in the target. These backgrounds can only affect the low energy end of the spectrum.

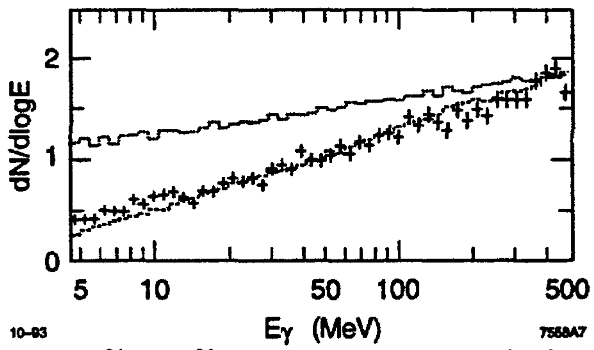

FIG. 7. The difference between the 3% and 5% uranium target spectra. The dotted histogram is the BH Monte Carlo, the dashed histogram the LPM Monte Carlo, and the crosses are data.

The calorimeter calibration uncertainty of 10% is equivalent to shifting the histogram contents sideways by one bin. The energy uncertainty affects the cross section measurement with a magnitude depending on the slope of the curve $d\sigma/d\log(E_\gamma)$; for the 5% X_0 uranium target, it contributes a 2.5% uncertainty in the cross section. Any errors in the cluster finding, either the inclusion of stray noise, or the omission of valid energy, will have a similar effect, but concentrated at the low end of the spectrum.

We measure the target length, width and mass, to find the thickness in g/cm^2, to 2% accuracy. Finding the actual density is less straightforward. Graphite can vary significantly in density; for the carbon targets we actually measured their thickness, to find their density, with an estimated 5% systematic error. The uranium targets are too thin and malleable to allow for an accurate thickness measurement; we assign a 1% systematic error to account for natural density variations. The thickness mainly affects the absolute normalization, while the density affects the size of the LPM suppression.

We believe that we know the electron flux to 3% at this point.

The Monte Carlo should represent the Migdal formulae within 3%, with most of the inaccuracy coming from the use of interpolations to the data points calculated by Migdal. This can be reduced in the future by using better approximations [4].

These errors are large enough to account for the difference in normalization between the data and Monte Carlo discussed in the previous sections. When the effects of multiphoton pileup in the subtraction procedure are included, they are large enough to account for the discrepancy in Fig. 7 at low energies.

It is worthwhile to briefly discuss the accuracy in Migdal's calculation. Migdal uses a Fokker-Plank expansion to solve his differential equation. This approximation introduces an error of unknown size. We can, however, get one hint about his final accuracy by looking at his equations in the limit of no suppression; they should then match the BH formulae. Indeed, his equations do match BH to logarithmic accuracy. More quantitatively, for large photon energies, they agree to within 5%.

E. Longitudinal Density Effect

In addition to the data described above, we took some data with the calorimeter gain increased by roughly a factor of 10. This allowed us to study the bremsstrahlung spectrum down to 500 keV, where the longitudinal density effect introduces a large suppression. Because the longitudinal density effect is far less X_0 sensitive than the LPM effec

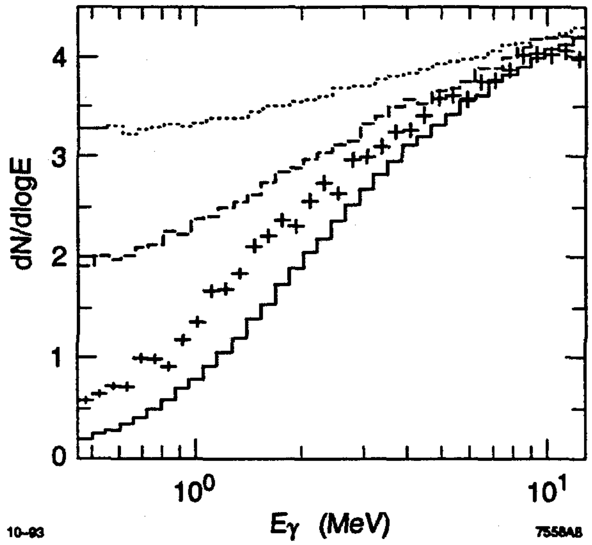

FIG. 8. Bremsstrahlung photon spectrum from 6% X_0thick carbon target, in the energy range 500 keV to 10 MeV. Shown are three Monte Carlo results, BH (dotted histogram), LPM only (dot-dashes), and LPM with dielectric suppression (dashes), in addition to the data(crosses).

longitudinal density suppression can be seen most clearly in light targets, so we will concentrate here on the carbon targets.

Before proceeding, it is worthwhile to point out that the experimental conditions are significantly different from those at higher energies. The experimental backgrounds, especially synchrotron radiation, are quite large. The calorimeter functions quite differently, with the dominant energy loss being by Compton scattering, with most of the energy confined to a single crystal. In contrast, at higher energies, loss is via pair production and electromagnetic showers, which spread over a larger region. These conditions call for different data analysis strategies to reduce the backgrounds.

Most of the synchrotron radiation from our spectrometer magnet occurs in a narrow strip downward from the center of the calorimeter. We can eliminate most of the it by requiring that the center of gravity of the calorimeter energy cluster be above the midpoint of the calorimeter. Also, because of the smaller energy deposition size, tighter cluster cuts were used in the analysis.

These cuts lead to Fig. 8, showing the spectrum from a 6% carbon target. Below 5 MeV, the data drops rapidly. Also shown for comparison are results from three Monte Carlo calculations: BH, LPM only, and LPM with dielectric suppression. The data is between the LPM only and LPM with dielectric suppression results.

There are a number of possible reasons for the disagreement: remaining backgrounds, calorimeter effects, and other photon sources. The remaining backgrounds are the small remaining synchrotron radiation and transition radiation, which can become significant below 1 MeV.

The calorimeter and electronics response is complicated for small signals. Calorimeter and electronic noise become more significant. Random and synchronous noise was greatly reduced by using a 5 ADC count (50 keV here) on the calorimeter readout for each crystal. This had the undesirable effect of eliminating some of the crystals from the calorimeter signal. At the low end of the range, the calorimeter light output of 1 photoelectron per 10 keV became problematic; The lower edge of Fig. 8, 500 keV, corresponds to 50 photoelectrons, so photoelectron statistics alone introduce a 14% uncertainty in the energy.

We are now evaluating these contributions in detail, but it is clear that there is significant suppression at low energies. As a check that it isn't entirely due to the LPM effect, we have studied some of the data taken with 8 GeV electrons. Because the LPM energy scales as the beam energy squared, whereas the minimum density suppression energy only scales as the beam energy, at 8 GeV LPM suppression should be minimal, but longitudinal density suppression should remain. This data shows that the falloff remains, and so should be due to the longitudinal density effect.

VII. CONCLUSIONS

We have measured the bremsstrahlung photon spectrum from 25 GeV electrons in thin targets of a variety of materials. For photons with energies of 5 to 500 MeV, the bremsstrahlung spectrum matches that predicted by Landau, Pomeranchuk, and Migdal. For very thin targets, the suppression is reduced or eliminated, as predicted by theory.

We see qualitative evidence for longitudinal density suppression.

A detailed analysis is in progress; we expect a final experimental precision of a few percent, matching the accuracy of the calculations.

ACKNOWLEDGMENTS

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